TI Designs: TIDA-01486

Ultrasonic Flow Transmitter Reference Design

Description

This reference design features an ultrasonic flow transmitter that is able to measure water flow in the large pipes used in the process industry. The reference design can drive four different Piezo transducers with up to 2 MHz ±12-V pulses and amplify the ultrasonic signal received from these up to 50 dB.

The reference design leverages the MSP430FR6047 microcontroller (MCU) which offers an integrated Ultrasonic Sensing Solution (USS) module with high-speed ADC-based signal acquisition followed by an optimized digital-signal processing using the integrated Low-Energy Accelerator (LEA) module to deliver a high-accuracy metering solution with ultra-low power.

Resources

TIDA-01486	Design Folder
MSP430FR6047	Product Folder
THS3095	Product Folder
TS5A3357	Product Folder
SN74LVC1G08	Product Folder

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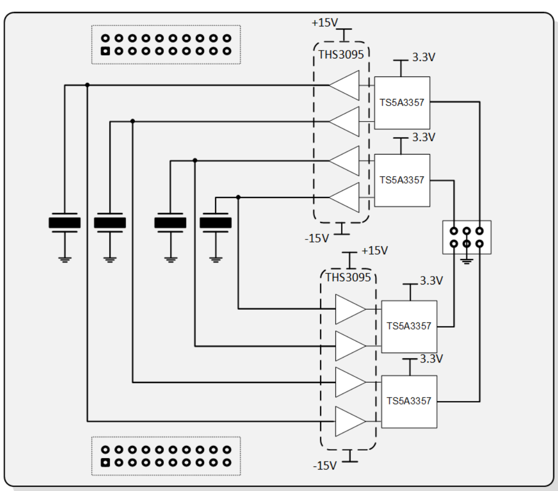
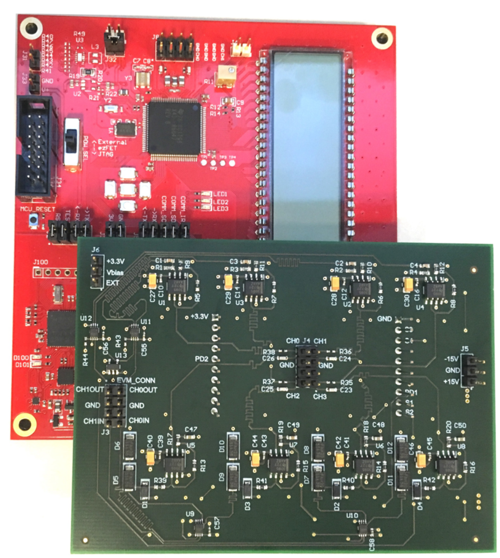
Features

- Able to Drive 4 Piezo Transducer (2 MHz, up to ±12 V)
- Up to 50-dB Gain
- High-Speed ADC-Based Signal Acquisition
- High Accuracy : 50ps ZFD
- Low Power

Applications

- Ultrasonic Flow Transmitter
- Water Meter
- Gas Meter





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1 System Description

1.1 Key System Specifications

Table 1 lists the key system specifications.

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Sensor type	Piezoelectric Transducer	
# of transducer pair	2	
Transducer driving voltage	Up to ±12V	
Zero Flow Drift	Approximately 50 ps	
Single shot STD deviation	Approximately 40 ps	
Total gain	50 dB	
Temperature Range	–40°C to 85°C	

2 System Overview

2.1 Block Diagram

Figure 1 shows the TIDA-01486 block diagram.

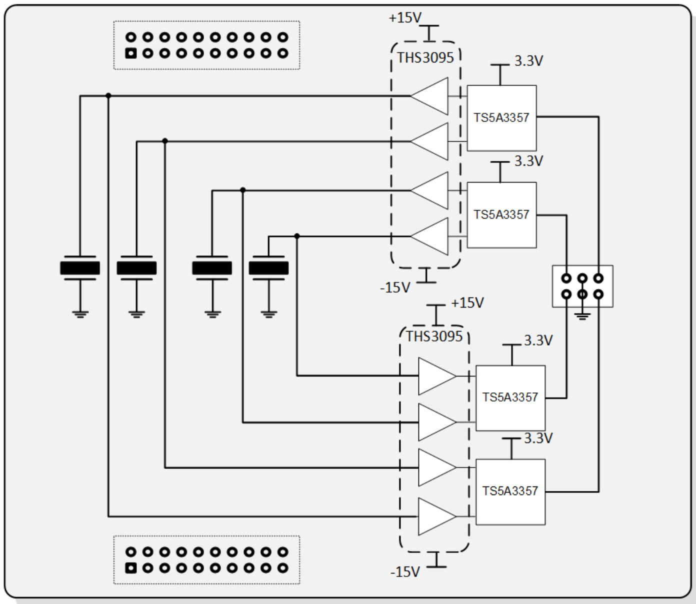


Figure 1. TIDA-01486 Block Diagram

2.2 Design Considerations

This reference design is in a BoosterPack™ plug-in module form factor which can be plugged into the MSP430FR6047 EVM. The board features a driving stage, a receiving stage, and a switching stage which add the following benefits to the MSP430FR6047 MCU:

- Additional pair of transducers
- Additional 20-dB gain
- Driving voltage up to ±12 V

The TIDA-01486 is enabled to control 2 pairs of transducers by driving and receiving them with four different high-speed op amps.

The following sections analyze the design considerations taken for the different stages.

2.2.1 Driving Stage

Each transducer can act as a transmitter and receiver. The transducers are driven one by one, pair by pair sequentially.

To drive each transducer an high speed, a low impedance driver able to provide up to ±12 V is required.

The THS3095 is a very good fit for this purpose due to its wide supply range from ±5 V to ±15 V combined with its wide bandwidth 210 MHz with a 100-Ω load.

Another good feature of this device is the power shutdown feature that puts the amplifier in low-power standby mode, and lowers the quiescent current from 9.5 mA to 500 µA.

Indeed, all the op amps will be on when transmitting and receiving. However, this happens only at regular intervals. The rest of the time, the whole AFE could be powered down or even turned off completely.

Four THS3095s were used in the TIDA-01486 to drive two transducer pairs.

2.2.2 Receiving Stage

It is important that the receiving and transmitting op amps are the same. Having different op amp chips in the two directions would mean there will be a differential time of flight delay, even in zero flow.

Additionaly, in this particular configuration the receiving op amp cannot be low voltage because it could be damaged when hit by the ±12-V transmitting signal since the receiving and transmitting stage share the same path (see Figure 1).

This is why the THS3095 devices are selected for the receiving stage.

A non-inverting configuration stage was selected for the amplifier. The recommended resistor values table in *High-Voltage, Low-Distortion, Current-Feedback Operational Amplifiers* shows the recommended resistor values for optimum frequency response. In this case, a 20-dB gain is selected so 95.3 Ω and 866 Ω are used considering ±15-V supply voltage (see Figure 2).

At the receiving signal, a 750-mV bias voltage is needed to cover the full range of the MSP430FR6047 MCU. The bias voltage is generated by R8 and R7 (see Figure 2). Putting a DC bias on the output of the RX op amp allows the use of a regular single-supply MUX. No negative supply is required.

The signal is clamped and after that is amplified to avoid damage to the switch and MSP430FR6047 MCU in case the signal is higher than what their input pins can withstand. For the signal clamping action, a Schottky diode (SD1) for the low-side clamping and three silicon diodes (D1, D2, and D3) for the high-side clamping are used (see Figure 2).

A capacitor (C3) in series with the feedback resistor to ground allows removal of the DC bias voltage removed from the op amp gain equation (see Figure 2).

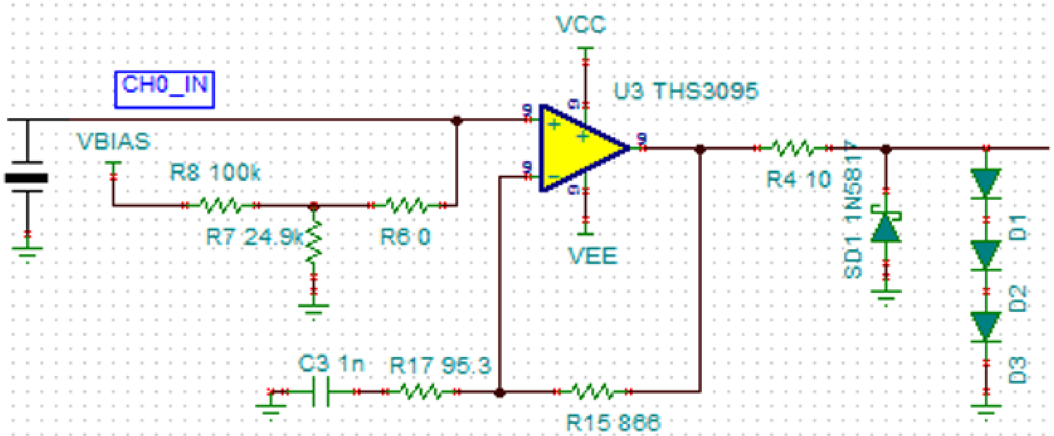


Figure 2. TIDA-01486 Receiving Stage

2.2.3 Switching Stage

For the receiver side and transmitting side, switches are needed to select the RX and TX path.

One of the main features of the switching stage is the low on-state resistance (R_{on}) because of the low impedance which characterizes the ultrasonic transducer. Consider a transmit frequency of 2 MHz and a typical transducer capacitor of 1 nF R << ½πfC = 80 Ω to not influence the measurement.

The TS5A3357 device, a single 5-Ω analog switch, is selected for the switching stage.

The two pairs are driven as follows:

- Pair 1 upstream: EVM_CH0_OUT ➡ CH0_T, CH1_R ➡ EVM_CH1_IN
- Pair 1 downstream: EVM_CH1_OUT ➡ CH1_T,CH0_R ➡ EVM_CH0_IN

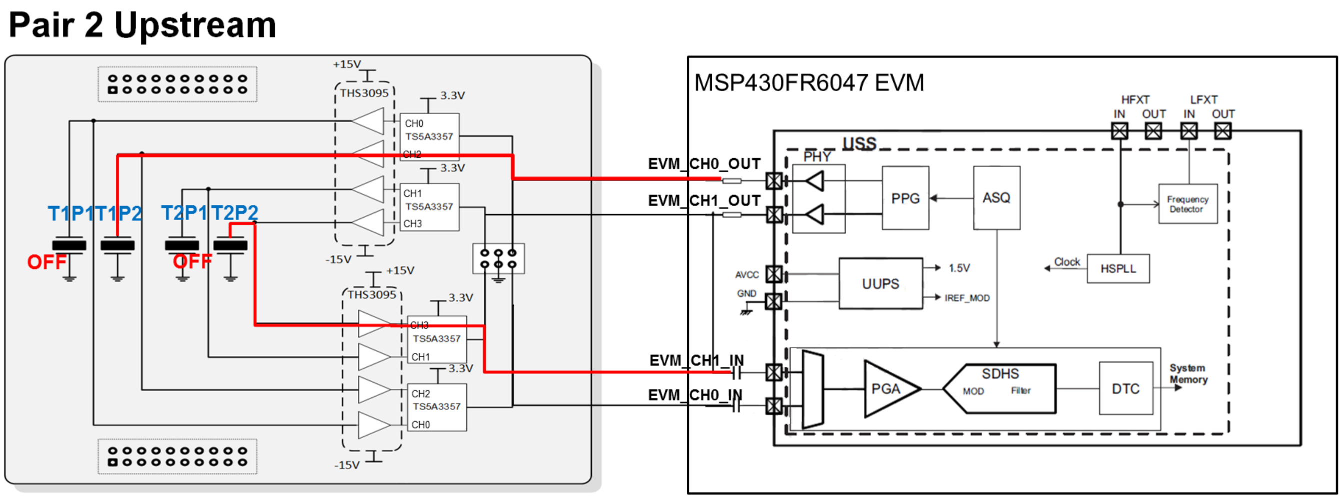


Figure 3. Pair 1 Upstream

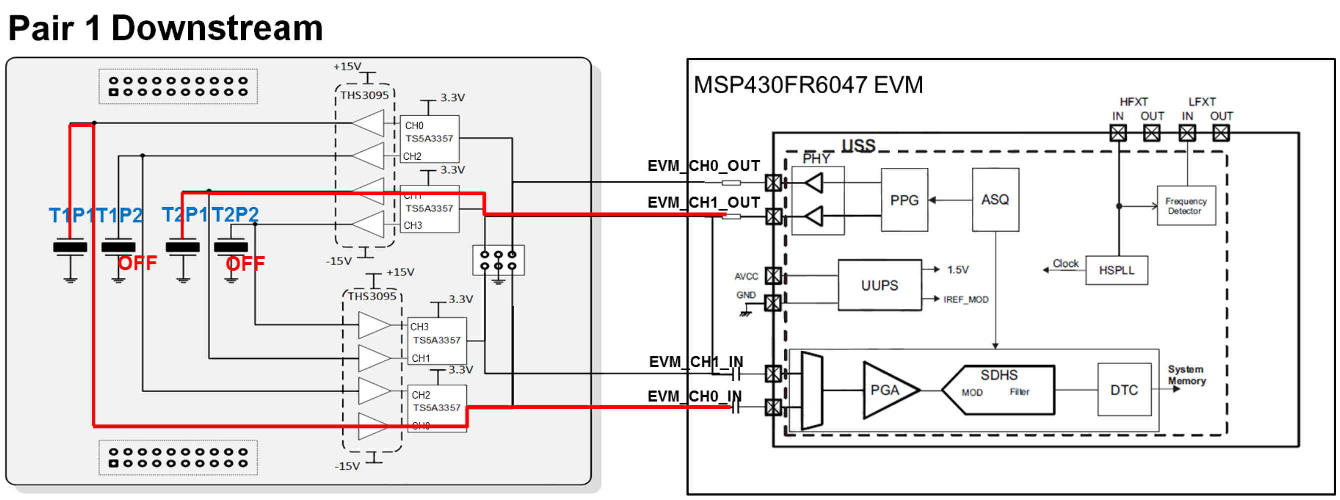


Figure 4. Pair 1 Downstream

- Pair 2 upstream: EVM_CH0_OUT ➡ CH2_T, CH3_R ➡ EVM_CH1_IN
- Pair 2 downstream: EVM_CH1_OUT ➡ CH3_T, CH2_R ➡ EVM_CH0_IN

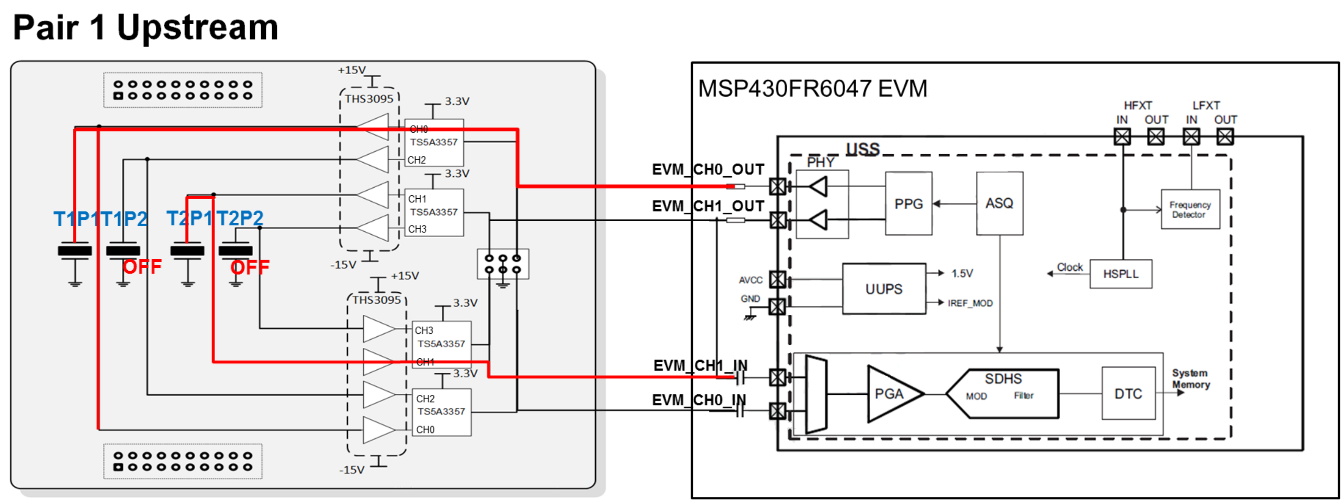


Figure 5. Pair 2 Upstream

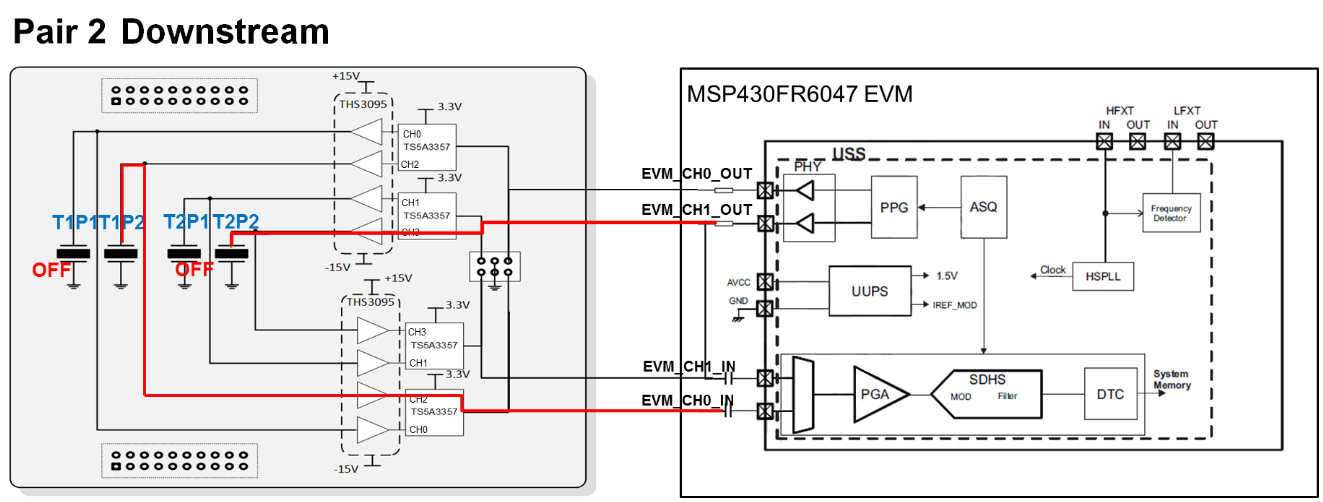


Figure 6. Pair 2 Downstream

Table 2 is used to control the switch and the shutdown pin of the op amps. S1, S2, S3, S4, PD1, and PD2 are GPIOs from the MSP430FR6047 that control, respectively, the switches and the op amps (see Figure 7).

Table 2. Switching Stage Truth Table

	S1	S2	S3	S4	PD1	PD2
Pair 1	1	0	1	0	1	0
Pair 2	0	1	0	1	0	1

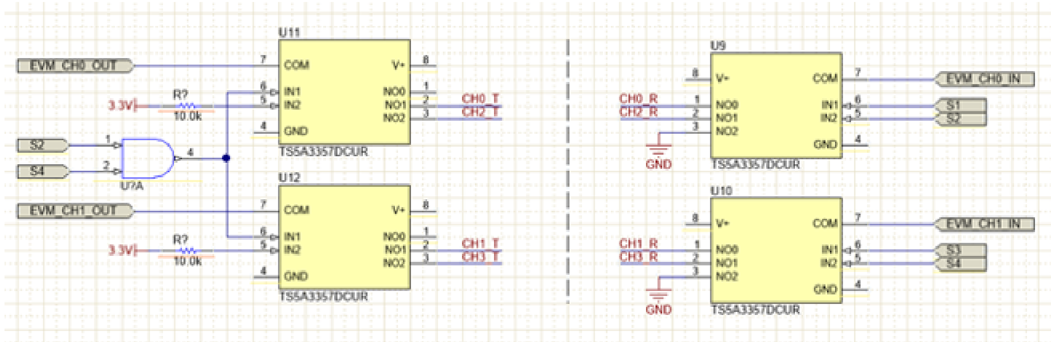


Figure 7. Switching Stage

2.2.4 Impedance Matching

Impedance matching is very important for this type of application. For impedance matching to work, everything from each transducer pin back into the board must look as much the same as possible.

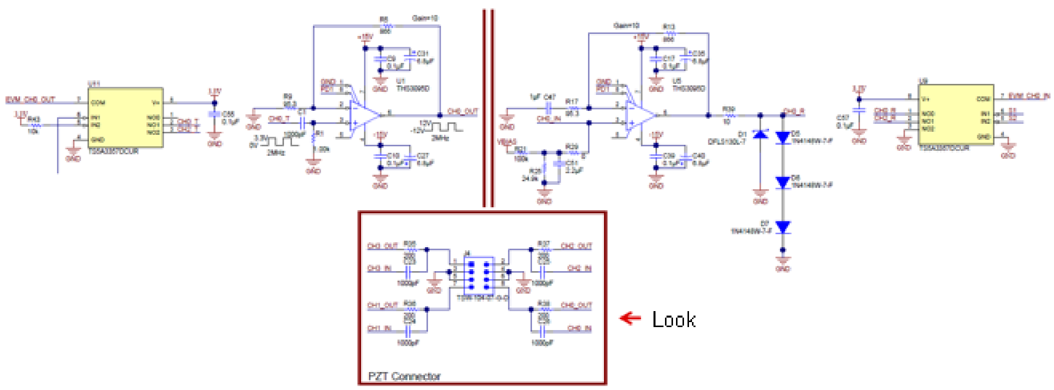


Figure 8. Transducer Pin View for Impedance Matching

Matching from the Point of View of the Transducer:

- Make your point of view the same as the transducer signal pin and look backwards into the board. The impedance should be the same when transmitting and receiving.
- For the TIDA-01486 when transmitting the output impedance of U1 via the 200-Ω resistor and the U5 input impedance and bias via the 1000-pF capacitor is seen.
- When receiving the output impedance of U1 via the 200-Ω resistor and the U5 input impedance and bias via the 1000-pF capacitor is seen
- The two points of view, when transmitting and receiving, are the same.

Are the impedances the same for TX and RX?:

- Because active components are used, the impedance may change with the signal.
- The output impedance of U1 is 0.06 Ω (from the device data sheet).
- The input impedance of U5 may be slightly different when hitting it with a large square wave signal versus when using the small signal due to the RX signal. When it sees the large square wave, U5 goes into saturation because of the gain, even though the output is limited with diodes.
- Since U5 is used in the non-inverting configuration, the transducer only sees the 1.3-MΩ (from the device data sheet) input impedance. If U5 were in the inverting configuration, the feedback resistors would come into play. The input impedance is also large compared to the biasing resistors. .

Other Sources of Impedance Mismatch:

- Active component package variation regardless of signal input. The THS3095 device is a high-speed op amp, so chip-to-chip variations are very low.

- Passive component variation – Use 1% resistors(especially for the 200 Ω), and 5% (X7R or better) capacitors.
- Board Layout – Match trace lengths, use symmetry for channel paths. The narrower the TX and RX trace widths, the less the parasitic capacitive effects; however, inductance increases. Pour a GND fill on the power layer, so that all the signal traces see a GND plane under it.
- From each transducer pin, look back into the board and everything should look as much the same as possible. Impedance mismatch causes zero flow offset drift to vary greatly with temperature.
- Match the trace lengths of the paths from the MUXes to the MSP430FR6047 MCU header so that there are no fixed-delay differences from channel to channel requiring calibration.

2.3 Highlighted Products

2.3.1 MSP430FR6047

Description

TI's MSP430FR604x and MSP430FR603x family of ultrasonic sensing and measurement SoCs are powerful, highly-integrated MCUs that are optimized for water and heat meters. The MSP430FR604x MCUs offer an integrated USS module, which provides high accuracy for a wide range of flow rates. The USS module helps achieve ultra-low-power metering combined with lower system cost due to the maximum integration requiring very few external components. MSP430FR604x and MSP430FR603x MCUs implement a high-speed ADC-based signal acquisition followed by optimized digital signal processing using the integrated LEA module to deliver a high-accuracy metering solution with ultra-low power, optimum for battery-powered metering applications.

The USS module includes a programmable pulse generator (PPG) and a physical interface (PHY) with a low-impedance output driver for optimum sensor excitation and accurate impendence matching to deliver best results for zero-flow drift (ZFD). The module also includes a programmable gain amplifier (PGA) and a high-speed 12-bit 8-Msps sigma-delta ADC (SDHS) for accurate signal acquisition from industry-standard ultrasonic transducers. Additionally, MSP430FR604x and MSP430FR603x MCUs integrate other peripherals to improve system integration for metering. The devices have a metering test interface (MTIF) module to implement pulse generation to indicate flow measured by the meter. The MSP430FR604x and MSP430FR603x MCUs also have an on-chip 8-MUX LCD driver, an RTC, a 12-bit SAR ADC, an analog comparator, an advanced encryption accelerator (AES256), and a cyclic redundancy check (CRC) module. MSP430FR604x and MSP430FR603x MCUs are supported by an extensive hardware and software ecosystem with reference designs and code examples to quickly start a design. Development kits include the MSP-TS430PZ100E 100-pin target development board and EVM430-FR6047 ultrasonic water flow meter EVM. TI also provides free software including the ultrasonic sensing design center, ultrasonic sensing software library, and MSP430Ware software. TI's MSP430 ultra-low-power (ULP) FRAM microcontroller platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, letting system designers increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatility of flash.

Figure 9 shows the MSP430FR6047 functional block diagram.

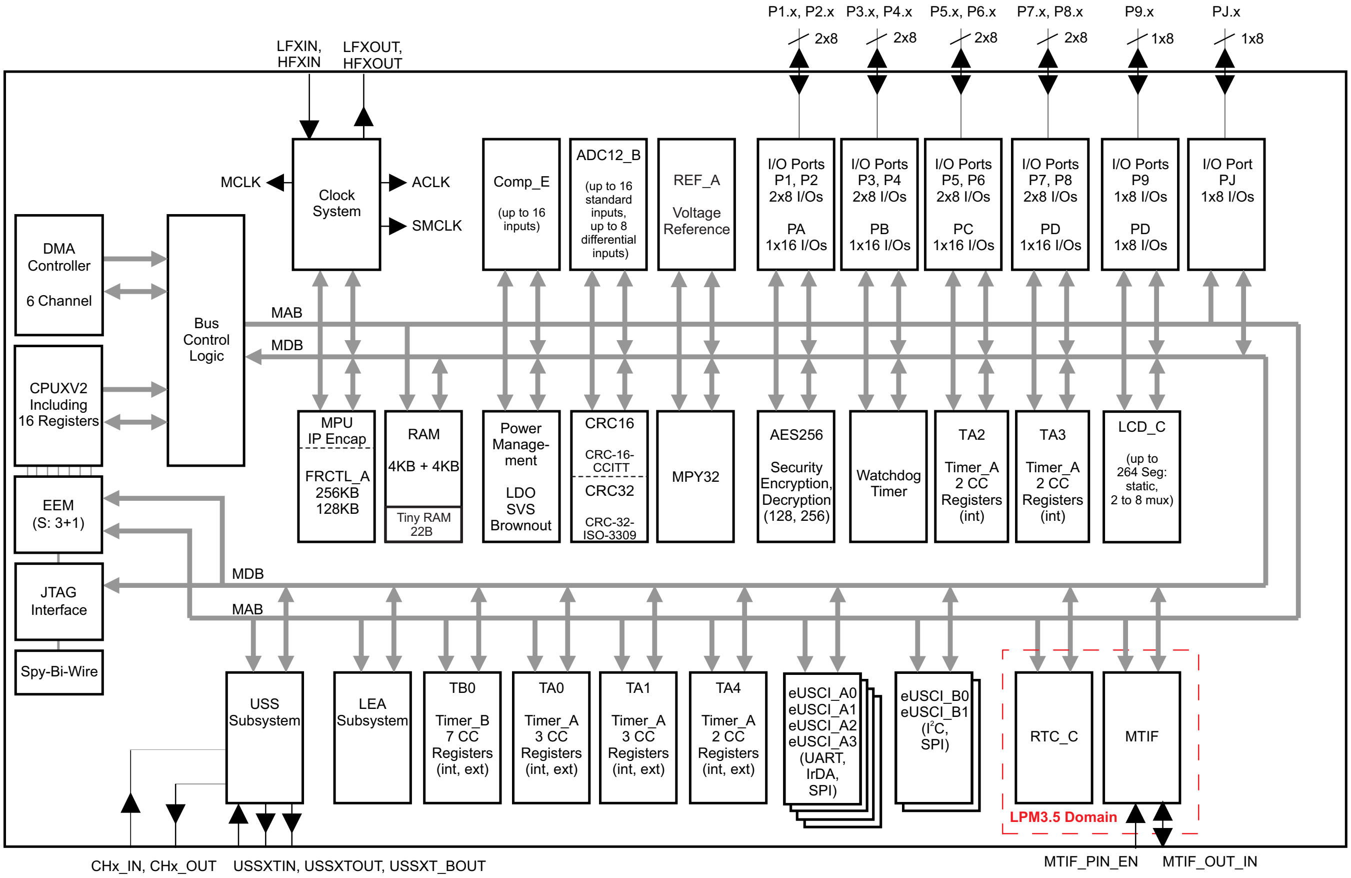


Figure 9. MSP430FR6047 Functional Block Diagram

Features

- < 25-ps Differential Time-of-Flight (dTOF) Accuracy
- High-Precision Time Measurement Resolution of < 5 ps
- Ability to Detect Low Flow Rates (< 1 Liter per Hour)
- Approximately 3-µA Overall Current Consumption With One Measurement per Second
- Compliant to and Exceeds ISO 4064, OIML R49, and EN 1434 Accuracy Standards
- Ability to Directly Interface Standard Ultrasonic Sensors (up to 2.5 MHz)
- Integrated Analog Front End (AFE) – Ultrasonic Sensing Solution (USS)
  - Programmable Pulse Generation (PPG) to Generate Pulses at Different Frequencies
  - Integrated Physical Interface (PHY) With Low-Impedance (4-Ω) Output Driver to Control Input and Output Channels
  - High-Performance High-Speed 12-Bit Sigma-Delta ADC (SDHS) With Output Data Rates up to 8 Msps
  - Programmable Gain Amplifier (PGA) With –6.5 dB to 30.8 dB
  - High-Performance Phase-Locked Loop (PLL) With Output Range of 68 MHz to 80 MHz
- Metering Test Interface (MTIF)
  - Pulse Generator and Pulse Counter
  - Count Capacity up to 65535 (16 Bit)
  - Operates in LPM3.5 With 200 nA (Typical)
- Low-Energy Accelerator (LEA)

- Operation Independent of central processing unit (CPU)
- 4KB of RAM Shared With CPU
- Efficient 256-Point Complex FFT:
  Up to 40 × Faster Than Arm® Cortex®-M0+ Core

- Embedded Microcontroller
  - 16-Bit RISC Architecture up to 16-MHz Clock
  - Wide Supply Voltage Range:
    2 V to 3.6 V [(1)]
- Optimized Ultra-Low-Power Modes
  - Active Mode: Approximately 120 µA/MHz
  - Standby Mode With Real-Time Clock (RTC) (LPM3.5): 450 nA [(2)]
  - Shutdown (LPM4.5): 30 nA
- Ferroelectric Random Access Memory (FRAM)
  - Up to 256KB of Nonvolatile Memory
  - Ultra-Low-Power Writes
  - Fast Write at 125 ns Per Word (64KB in 4 ms)
  - Unified Memory = Program + Data + Storage in One Space
  - 10^{15} Write Cycle Endurance
  - Radiation Resistant and Nonmagnetic
- Intelligent Digital Peripherals
  - 32-Bit Hardware Multiplier (MPY)
  - 6-Channel Internal DMA
  - RTC With Calendar and Alarm Functions
  - Six 16-Bit Timers With up to Seven Capture or Compare Registers Each
  - 32-Bit and 16-Bit Cyclic Redundancy Check (CRC)
- High-Performance Analog
  - 16-Channel Analog Comparator
  - 12-Bit SAR ADC Featuring Window Comparator, Internal Reference, and Sample-and-Hold, up to 16 External Input Channels
  - Integrated LCD Driver With Contrast Control for up to 264 Segments
- Multifunction Input/Output Ports
  - All Pins Support Capacitive-Touch Capability With No Need for External Components
  - Accessible Bit-, Byte-, and Word-Wise (in Pairs)
  - Edge-Selectable Wake From LPM on All Ports
  - Programmable Pullup and Pulldown on All Ports
- Code Security
  - Random Number Seed for Random Number Generation Algorithms
  - IP Encapsulation Protects Memory From External Access
  - FRAM Provides Inherent Security Advantages
- Enhanced Serial Communication
  - Up to Four eUSCI_A Serial Communication Ports
    - UART With Automatic Baud-Rate Detection
    - IrDA Encode and Decode
  - Up to Two eUSCI_B Serial Communication Ports
    - I^2C With Multiple-Slave Addressing

(1) Minimum supply voltage is restricted by SVS levels.
(2) The RTC is clocked by a 3.7-pF crystal.

  - Hardware UART or I^2C Bootloader (BSL)
- Flexible Clock System
  - Fixed-Frequency DCO With 10 Selectable Factory-Trimmed Frequencies
  - Low-Power Low-Frequency Internal Clock Source (VLO)
  - 32-kHz Crystals (LFXT)
  - High-Frequency Crystals (HFXT)
- Development Tools and Software (see the tools and software section of the *MSP430FR604x(1), MSP430FR603x(1) Ultrasonic Sensing MSP430™ Microcontrollers for Water-Metering Applications* Data Sheet)
  - Ultrasonic Sensing Design Center Graphical User Interface
  - Ultrasonic Sensing Software Library
  - EVM430-FR6047 Water Meter Evaluation Module Board
  - MSP-TS430PZ100E Target Socket Board for 100-Pin Package
  - Free Professional Development Environments With EnergyTrace++ Technology
  - MSP430Ware™ for MSP™ Microcontrollers
- The device comparison section of the *MSP430FR604x(1), MSP430FR603x(1) Ultrasonic Sensing MSP430™ Microcontrollers for Water-Metering Applications* Data Sheet Summarizes the Available Device Variants and Package Options
- For Complete Module Descriptions, see the *MSP430FR58xx, MSP430FR59xx, and MSP430FR6xx Family User's Guide*

2.3.2 THS3095

Description

The THS3091 and THS3095 devices are high-voltage, low-distortion, high-speed, current-feedback amplifiers designed to operate over a wide supply range of ±5 V to ±15 V for applications requiring large, linear output signals such as pin, power FET, and VDSL line drivers.

The THS3095 device features a power-down pin ($\overline{PD}$) that puts the amplifier in low-power standby mode, and lowers the quiescent current from 9.5 mA to 500 µA.

The wide supply range combined with total harmonic distortion as low as –69 dBc at 10 MHz, in addition to the high slew rate of 7300 V/µs makes the THS309x ideally suited for high-voltage arbitrary waveform driver applications. Moreover, having the ability to handle large voltage swings driving into high-resistance and high-capacitance loads while maintaining good settling time performance makes the devices ideal for pin driver and power FET driver applications.

The THS3091 and THS3095 devices are offered in an 8-pin SOIC (D), and the 8-pin SOIC (DDA) packages with the PowerPAD™ integrated circuit package.

Features

- Low Distortion
  - 77-dBc HD2 at 10 MHz, R_L = 1 kΩ
  - 69-dBc HD3 at 10 MHz, R_L = 1 kΩ
- Low Noise
  - 14-pA/$\sqrt{Hz}$ Noninverting Current Noise
  - 17-pA/$\sqrt{Hz}$ Inverting Current Noise
  - 2-nV/$\sqrt{Hz}$ Voltage Noise
- High Slew Rate: 7300 V/µs (G = 5, V_O = 20 V_{PP})
- Wide Bandwidth: 210 MHz (G = 2, R_L = 100 Ω)
- High Output Current Drive: ±250 mA
- Wide Supply Range: ±5 V to ±15 V
- Power-Down Feature: THS3095 Only

2.3.3 TS5A3357

Description

The TS5A3357 device is a high-performance, single-pole triple throw (SP3T) analog switch that is designed to operate from 1.65 V to 5.5 V. The device offers a low on-state resistance and low input/output capacitance and thus, causes a very low signal distortion. The break-before-make feature allows transferring of a signal from one port to another, with a minimal signal distortion. This device also offers a low charge injection which makes this device suitable for high-performance audio and data acquisition systems.

Features

- Specified Break-Before-Make Switching
- Low On-State Resistance
- High Bandwidth
- Control Inputs Are 5.5-V Tolerant
- Low Charge Injection
- Excellent On-State Resistance Matching
- Low Total Harmonic Distortion (THD)
- 1.65-V to 5.5-V Single-Supply Operation
- Latch-Up Performance Exceeds 100 mA per JESD78, Class II
- ESD Performance Tested per JESD22
  - 2000-V Human-Body Model (A114-B, Class II)
  - 1000-V Charged-Device Model (C101)

2.4 System Design Theory

Ultrasonic sensing uses the time of flight (TOF) of an ultrasonic wave and its dependency on the flow rate of the medium to measure and calculate volume flow, using the difference in the propagation time of the ultrasonic wave when transmitted into and against the direction of the flow. This technology is outstanding at measuring volume flow rates across a wide range and works with fluids like water and oil as well as gases like air and methane. TOF-based ultrasonic meters measure flow rates based on the difference in propagation time of ultrasonic signals in the upstream and downstream directions. The ultrasound wave travels faster when traveling in the direction of the flow and slower when against the flow. This technology works whether the transducer pairs are located inside of a pipe or clamped to the outside of a pipe. This approach does require a direct path between the two transducers, requiring careful mechanical construction of the flow tube where the transducers are housed. The technology does not work in the presence of air bubbles, which lead to significant attenuation of the ultrasound signal. Because the propagation velocity of an ultrasound wave varies between a single fluid or a composition of multiple fluids in a mixture, TOF-based ultrasonic technology can also be used for material composition analysis.

2.4.1 Ultrasonic Flow Meter Configurations

TOF-based ultrasonic flow meters have two types of construction: in-line or clamp-on. In-line meters are intrusive flow meters where transducers are installed inside the flow tubes and make contact with the liquid; clamp-on flow meters are non-intrusive by installing the transducers on the surface of the pipe and sense the sound wave traveling through the pipe. Figure 10 shows in-line flow meters can be diagonal and give the transducers a direct line of sight.

Figure 11 shows a reflective in-line meter where the sound wave from a transmitting transducer reaches a second transducer only after reflection from a material on the surface of the pipe.

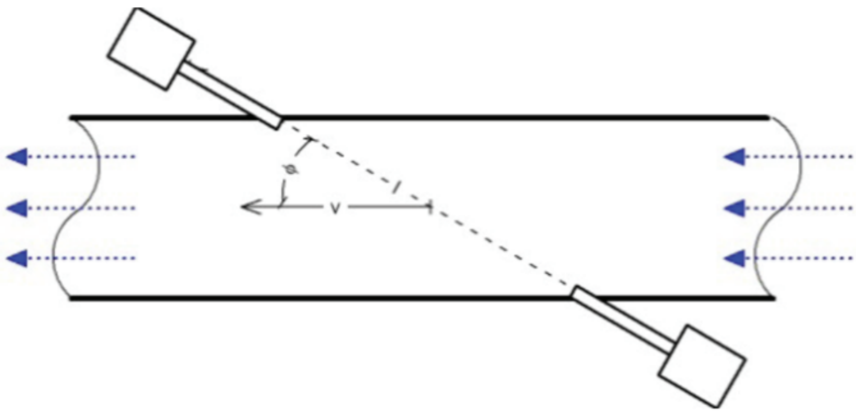


Figure 10. In-Line and Diagonal Transducer Placement

Figure 12 shows how some industrial flow meters with large diameter flow tubes use two pairs of transducers for improved performance, accommodating the larger attenuation that will occur with larger pipe diameters.

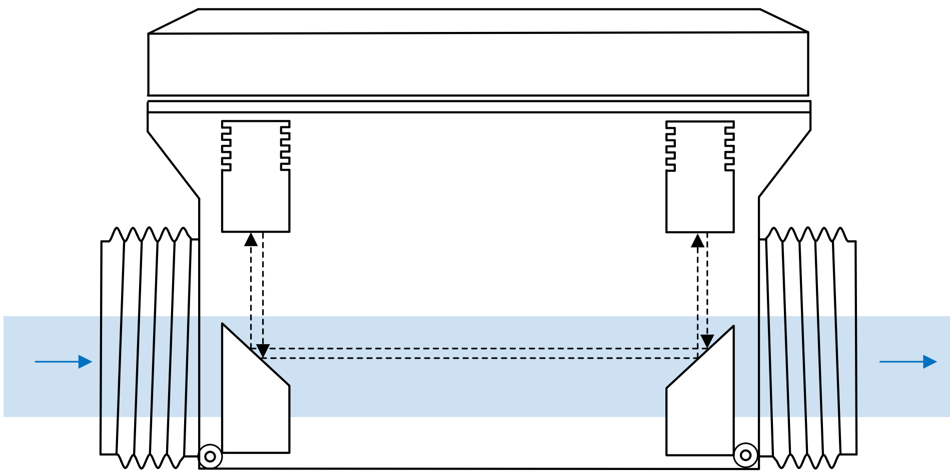


Figure 11. In-Line and Reflective Transducer Placement

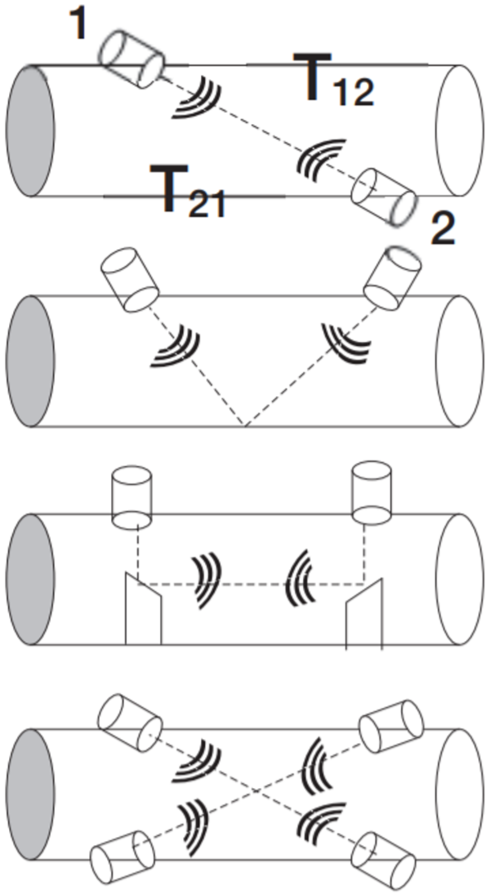


Figure 12. Various Configurations of In-Line Placement of Transducer Pairs

Figure 13 shows a clamp-on transducer placement that encounters additional signal attenuation because the ultrasonic wave needs to traverse through the pipe material. One of the key challenges associated with ultrasonic flow meters is maintaining accuracy over a wide range of flow rates, from a few liters per hour (lph) to tens of thousands of lph. Another challenge is maintaining flow-rate accuracy over fluid temperatures that can range from 0°C to 85°C, depending on the application. Because the velocity of an ultrasonic wave in fluid varies with the temperature of the fluid, the difference in propagation time to take flow-rate measurements will introduce errors when the fluid temperature changes.

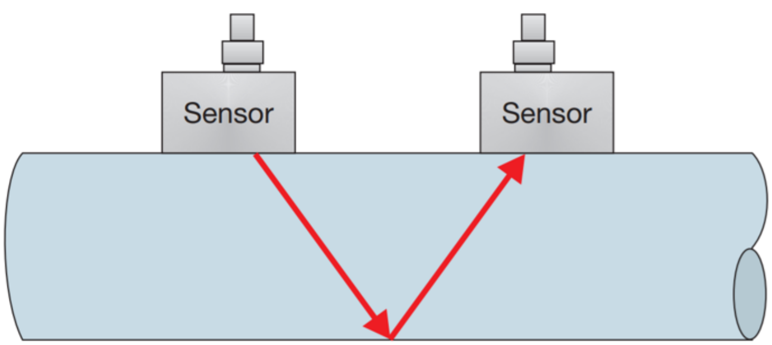


Figure 13. Clamp-On Transducer Placement

Figure 14 shows that the velocity of sound in water varies between 1,420 mps to 1,540 mps and is neither linear nor asymptotic in nature. In general, this can lead to errors in flow-rate estimation of more than 5 percent if you do not account for temperature. For improved accuracy, the system requires a temperature sensor. It is possible, however, to construct an alternate approach that takes measurements independent of temperature. This method entails obtaining the volume flow rate of a fluid using the absolute time of upstream and downstream propagation or TOF, in addition to the difference of the propagation.

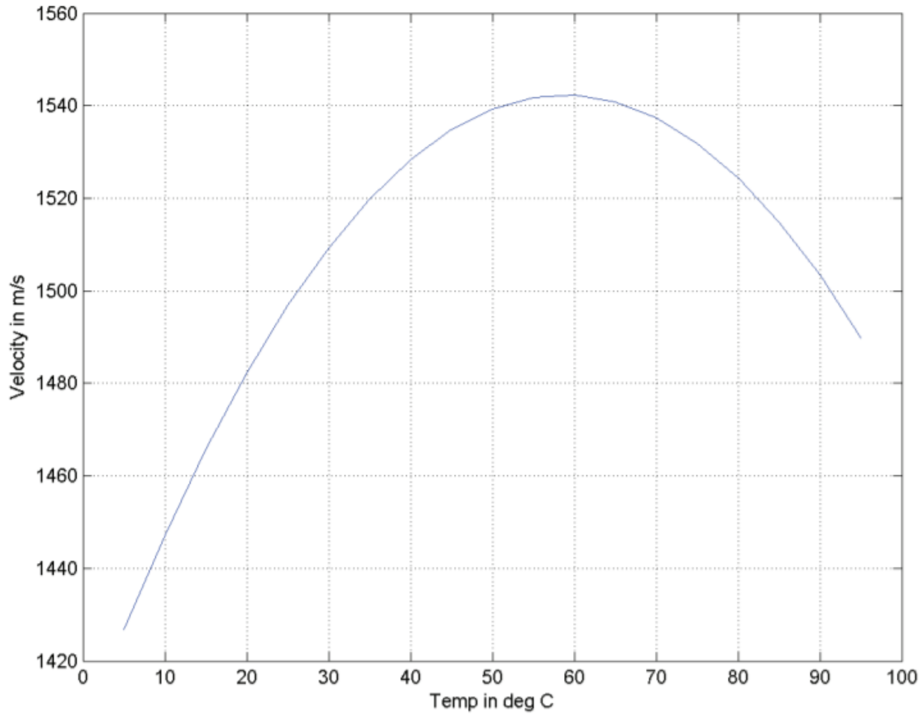


Figure 14. Ultrasound Velocity in Water as a Function of Water Temperature

2.4.2 Analog-to-Digital Converter (ADC)-Based Processing Advantages

Several different approaches can be used to obtain the difference in the upstream and downstream TOF. In the TIDA-01486 design, the approach that correlates the signal obtained after ADC to the signal received at the transducer is used. In the correlation-based ADC technique, the whole waveform is captured and stored for the signal received at the transducer for both the upstream and downstream measurements. Performing post-processing on the waveform determines the differential TOF.

The ADC-based approach has these inherent advantages:

- Performance – The correlation also provides low-pass filtering to suppress noise. This is implemented efficiently on the low-energy accelerator in TI's MSP430FR6047 MCU. The correlation approach results in a benefit of approximately 3–4 × noise lower standard deviation. The correlation filter also suppresses interference like line noise.
- Robustness to signal-amplitude variations – The algorithm based on the correlation technique, is insensitive to the received signal amplitude, transducer-to-transducer variation and temperature variation. Signal amplitude variation is observed frequently in high flow rates. Robustness is a significant advantage when transducer performance degrades over time, since some applications deploy flow meters for more than 10 years.
- ADC-based processing obtains the signal envelope naturally – The availability of the signal amplitude information enables tuning to the transducer frequencies. Also, you can use slow variations in the envelope across time to detect transducer aging. The ADC-based approach is also amenable to automatic gain control (AGC), which can boost the received signal if the transducer gain reduces over time (again, due to aging). As the correlation-based algorithm receives the amplified signal that maintains the output signal level, even with transducer aging, the system performance does not

degrade over time. Figure 15 is a functional block diagram of the correlation-based ADC approach, which requires the use of an ADC that oversamples the received signal.

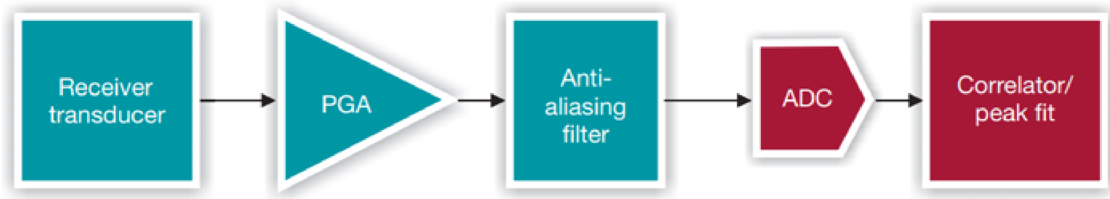
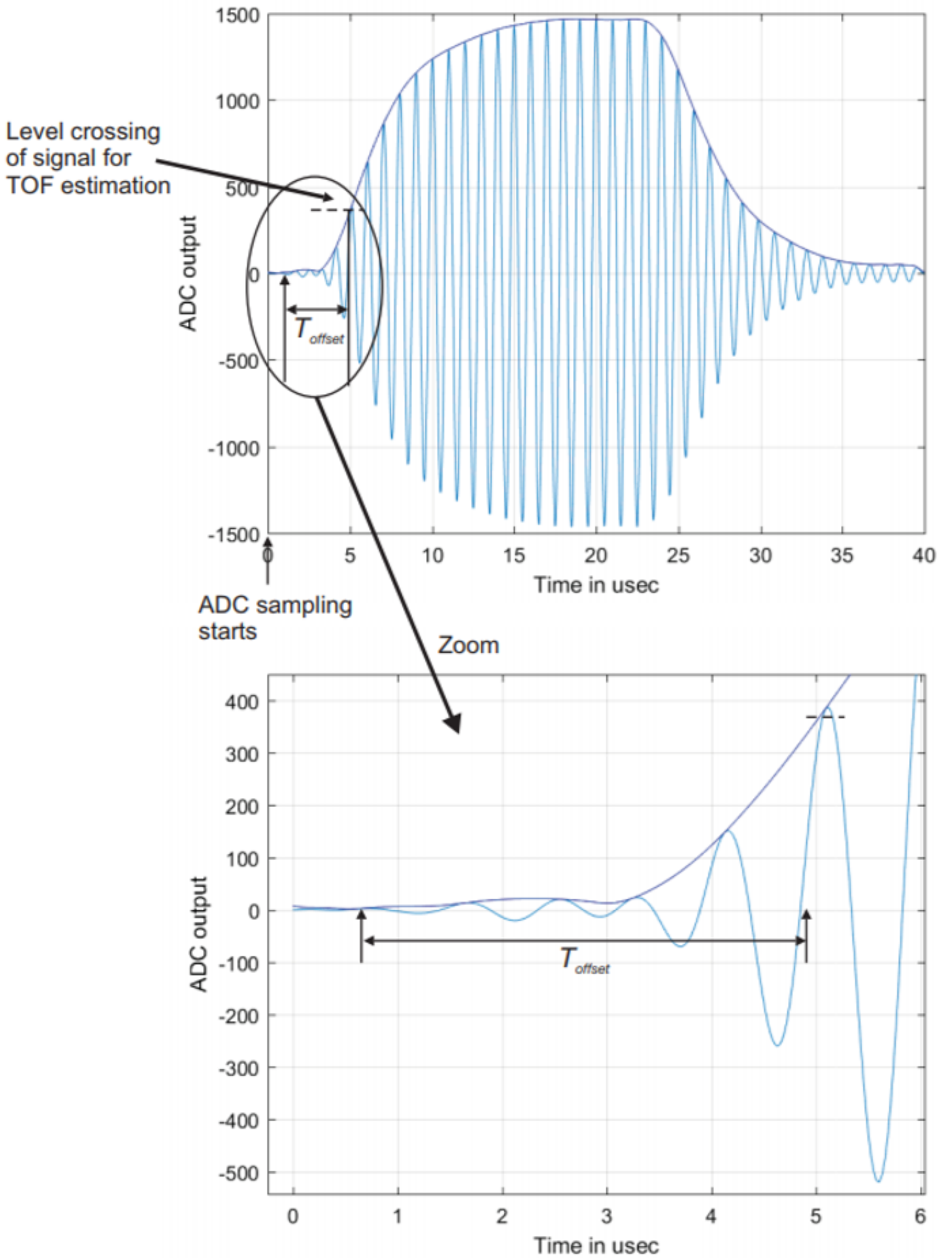


Figure 15. Correlation-Based Differential TOF Estimator

2.4.3 Absolute TOF Measurement

An absolute TOF measurement eliminates the need for a temperature sensor and the need to compute the velocity of sound in water. There are several approaches to calculating absolute TOF accurately. One approach computes the envelope of the received signal and the envelope crossing at a specified ratio to the maximum of the signal.

Figure 16 illustrates that the absolute TOF will be a constant offset from this threshold crossing of the envelope.



Zoomed-In Version of the Initial Waveform Cycles in the Bottom Panel

Figure 16. ADC-Captured Waveform and Envelope for Absolute TOF Calculation

2.4.4 MSP430FR6047 MCU Ultrasonic Sensing Module

The functional blocks that help achieve high performance for an ultrasonic flow meter application are part of an AFE called the USS IP block, which operates independently of the CPU of the MSP430 MCU . Figure 17 shows a conceptual block diagram. The ultrasonic-sensing module includes a universal USS power supply (UUPS), a power sequencer (PSQ), a PPG, a physical driver and PHY, a PGA, a high-speed phase-locked loop (HSPLL), a sigma-delta high-speed (SDHS) ADC, and an acquisition sequencer (ASQ). The ultrasonic-sensing module has its own power domain and can be powered ON and OFF independent of the other blocks on the MSP430FR6047 MCU. You can also reset it without affecting any of the other modules on the device. The impedance matching in the ultrasonic-sensing module is critical to obtain a very low drift in the delta time-of-flight measurement over time and any variation in water temperature. This also leads to the ability to detect very low flow rates.

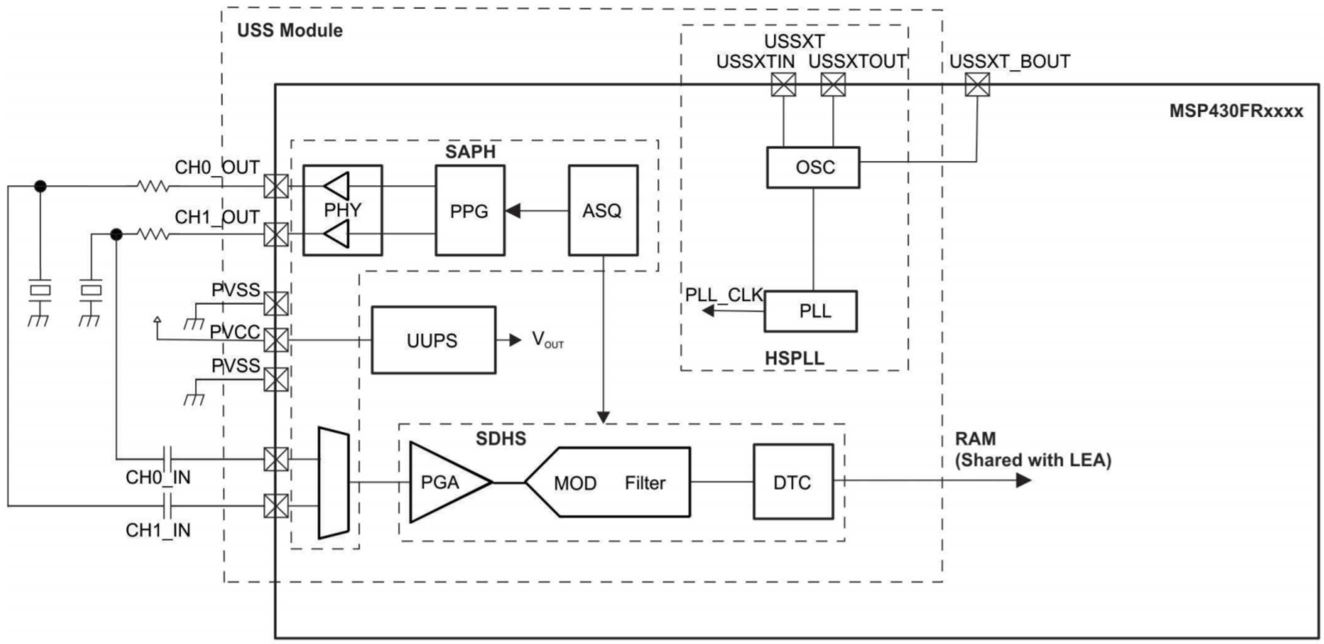


Figure 17. Ultrasonic-Sensing Solution Functional Block Diagram

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

Figure 18 illustrates the TIDA-01486 BoosterPack board connected to the MSP430FR6047 EVM through the BoosterPack connectors J1, J2.

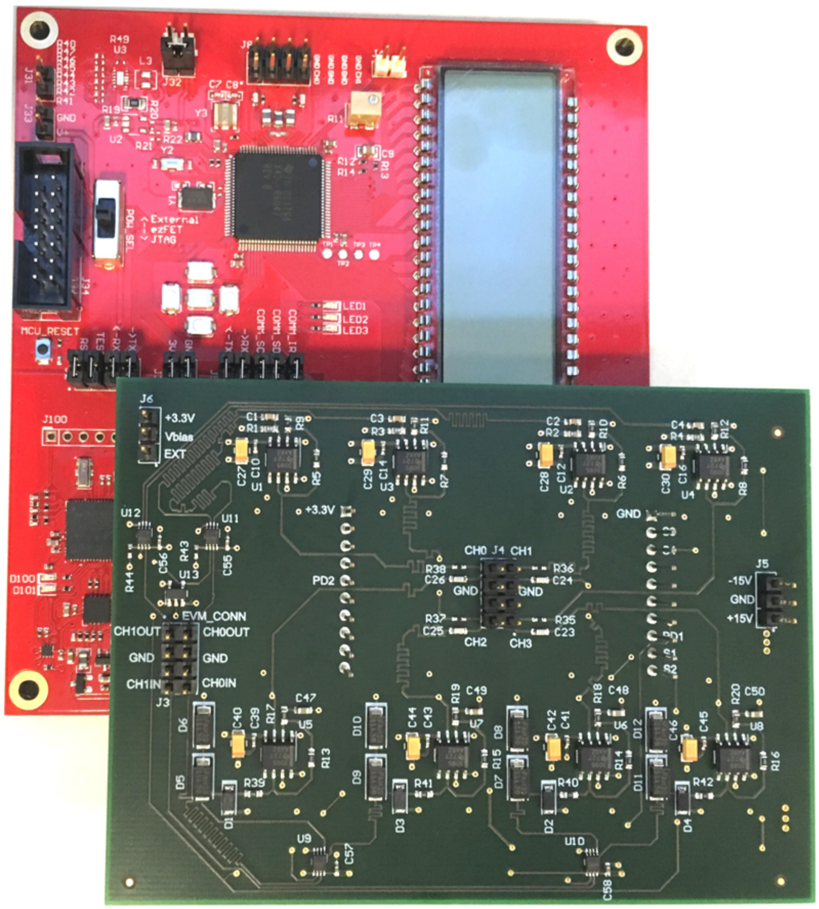


Figure 18. TIDA-01486 Connected to MSP430FR6047 EVM

Follow these steps to configure the TIDA-01486 (see Figure 19):

- The BoosterPack connectors provide the GPIOs to control the switches and op amps and the power supply, 3.3 V ,for the switches and logic.
- The bias voltage can be selected from connector J6, J7: internally, from the BoosterPack, or externally from a power supply.
- The power for the THS3095 device must be provided externally from the connector J5.
- The transmit and receive signals from the EVM must be connected to the TIDA-01486 through the connector J3.
- The external transducer must be connected to the connector J4.

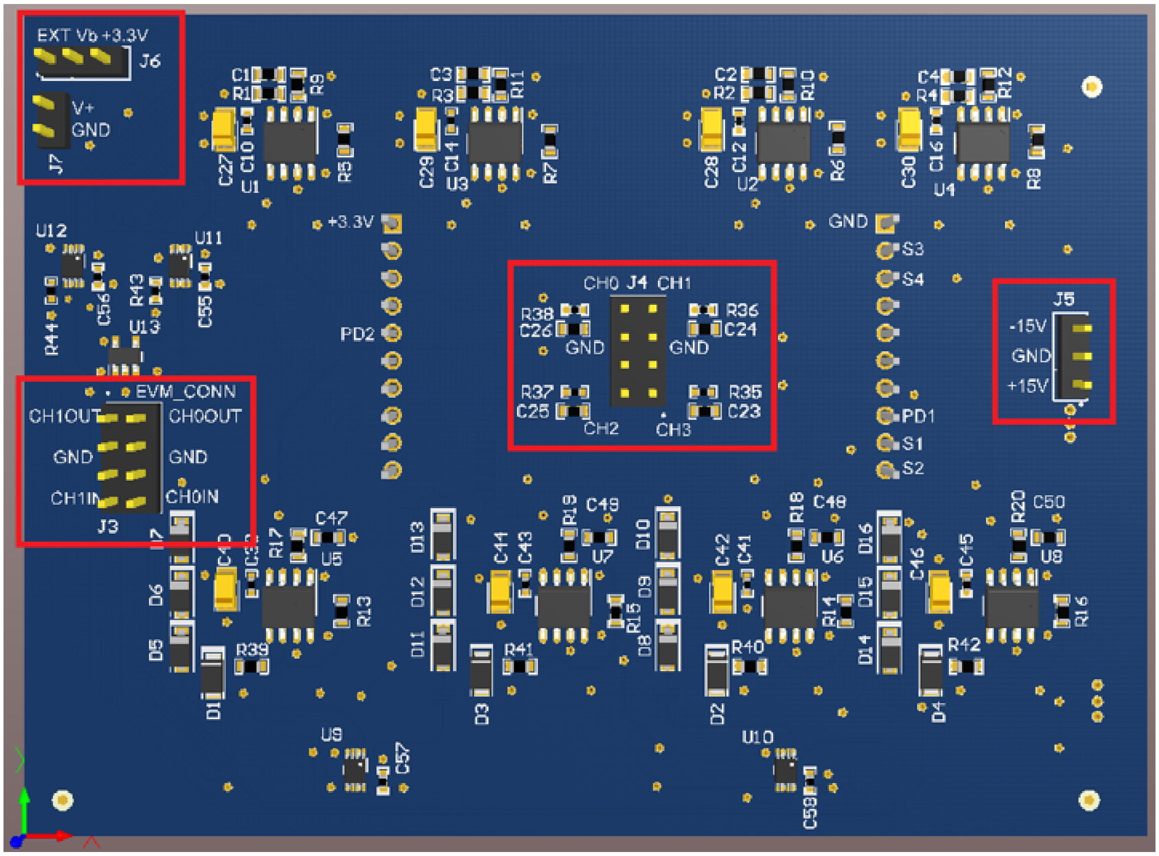


Figure 19. TIDA-01486 Hardware Configuration

On the MSP430FR6047 EVM, ensure that the jumpers are placed at the connector J30.

Once the previous steps are performed, connect the MSP430FR6047 EVM via USB to the computer.

The *MSP430 MCUs Ultrasonic Sensing Design Center* was used to take measurements.

Parameters must be set according the used transducers and mechanical setup.

3.2 *Testing and Results*

3.2.1 Test Setup

A 10-cm diameter pipe with 4 in-line transducers was used for the measurements.

For this particular pipe, the following hardware changes were done to the TIDA-01486:

- The transmit signal was lowered to ±6.6 V by amplifying only by 2 the signal coming from the MSP430FR6047 MCU. The op amp gain was changed by changing the resistors according to the recommended resistor values table in *High-Voltage, Low-Distortion, Current-Feedback Operational Amplifiers*. Section 2.2.3 shows the switching configuration.
- A gain of 7.9 dB (6-dB external + 1.9-dB internal) is enough for this particular test setup. The external gain was lowered to 6 dB by changing the resistors according to the recommended resistor values in *High-Voltage, Low-Distortion, Current-Feedback Operational Amplifiers*.

The following parameters were set in the GUI (see Figure 20).

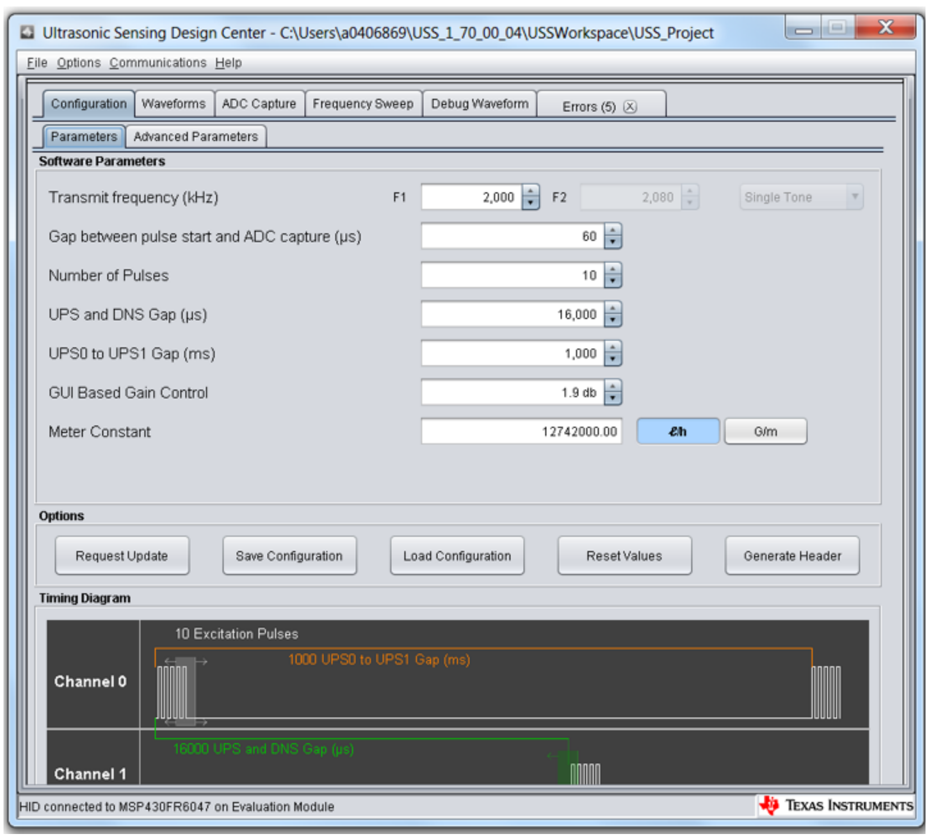


Figure 20. Configuration Parameters

3.2.2 Test Results

Figure 21 and Figure 22 show the ADC capture for pair 1 and pair 2, respectively.

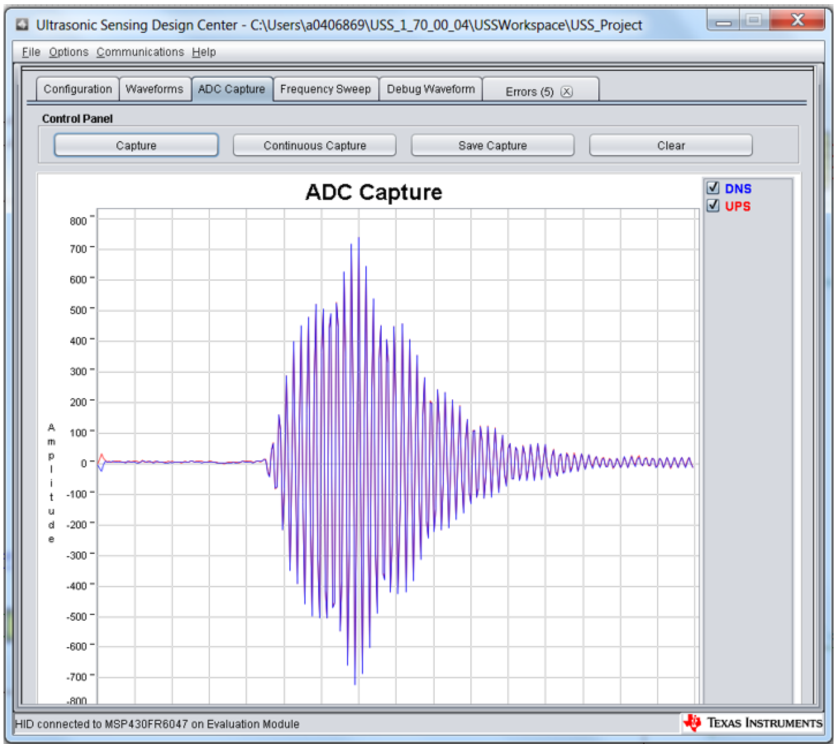


Figure 21. ADC Capture Pair One

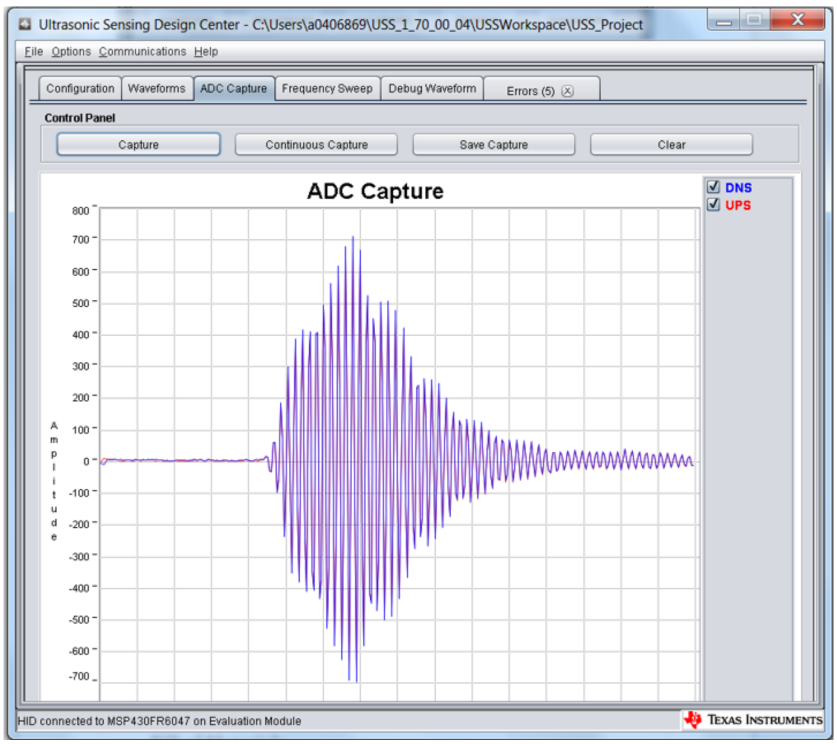


Figure 22. ADC Capture Pair Two

Offset drift for both pairs is around 50 ps. Single shot standard deviation is around 40 ps. Offset drift was calculated by taking the average of 200 measurements of delta TOF values. On that variable, the difference between the MAX and MIN to obtain the ZFD is performed. The measurements were taken over a time period longer than 5 hours.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01486.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01486.

4.3 PCB Layout Recommendations

Use the following TIDA-01486 PCB layout recommendations:

- Avoid vias for transmitting and receiving signals
- Remove polygon fills under the inputs and outputs on all op amps (Figure 23)
- Add a GND fill on layer Signal 2 if the open area has not being used. The GND fill helps CH2_OUT and CH1_IN because they have to go through vias to the bottom layer (Figure 24).
- Match trace lengths (Figure 25):
  - (CH0_OUT, CH0_IN, CH1_OUT, CH1_IN, CH2_OUT, CH2_IN, CH3_OUT, CH3_IN)
  - (CH0_T, CH1_T, CH2_T, CH3_T)
  - (CH0_R, CH1_R, CH2_R, CH3_R)
  - (EVM_CH0_IN, EVM_CH1_IN)
  - (EVM_CH0_OUT, EVM_CH1_OUT)

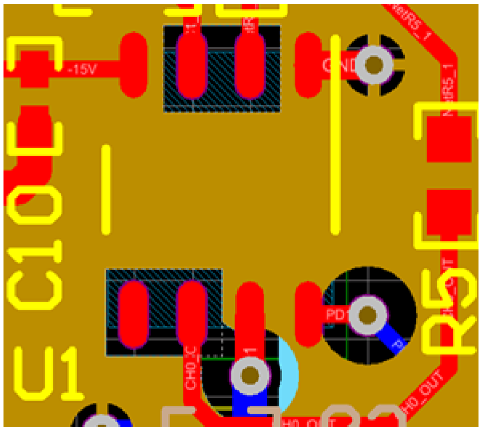


Figure 23. Op Amp Inputs and Outputs Test

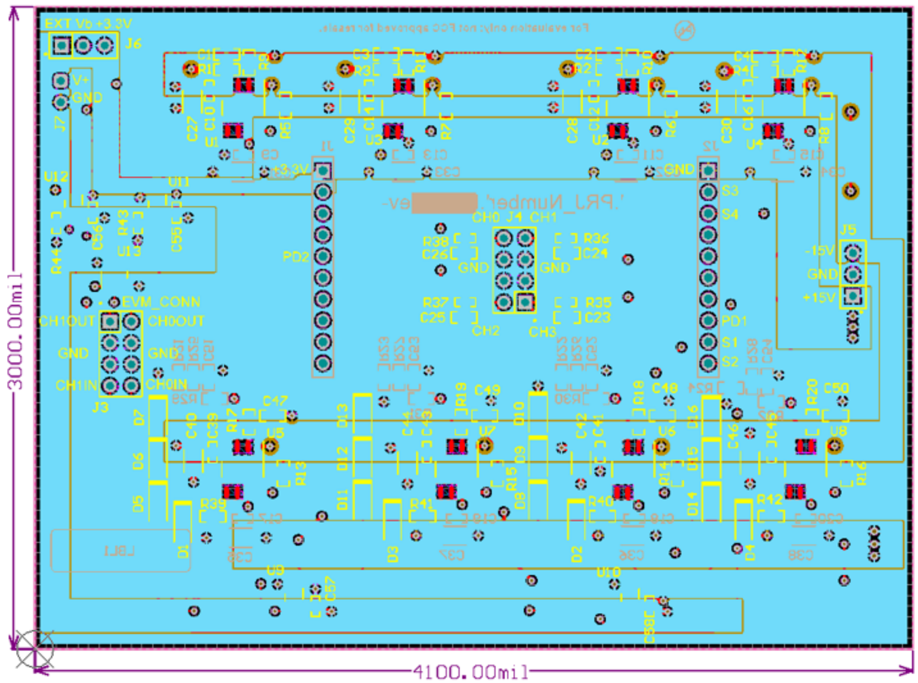


Figure 24. GND Fill on Layer Two

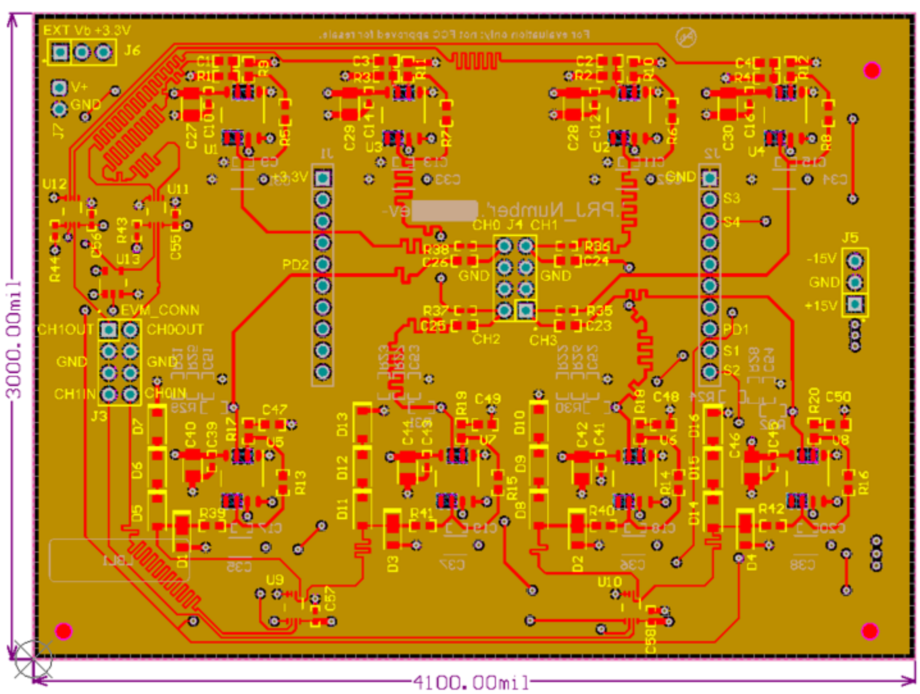


Figure 25. Match Trace Lengths

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01486.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01486.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01486.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01486.

5 Software Files

To download the software files, see the design files at TIDA-01486.

6 Related Documentation

1. Texas Instruments, *High-Voltage, Low-Distortion, Current-Feedback Operational Amplifiers Data Sheet*

6.1 Trademarks

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7 Acknowledgments

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8 About the Author

Giovanni Campanella is a systems engineer at Texas Instruments, where he is responsible for defining and developing reference design solutions for the industrial segment. He earned his bachelor's degree in electronic and telecommunication engineering at the University of Bologna and his master's degree in electronic engineering at the Polytechnic of Turin in Italy. He is an expert in sensors and analog signal chain.