TI Designs HVAC Coil Airflow Sensor for Predictive Maintenance in Air Filter Replacement Reference Design

Texas Instruments

Description

This TI Design provides a reference solution for monitoring airflow efficiency and temperature through HVAC systems. The design is used in conjunction with solid-state relays and piezoelectric vibration sensors to monitor and react accordingly to low airflow conditions through the air handler. The system also includes a calibration algorithm for consistent performance from system to system.

Resources

TI E2E[™] Community

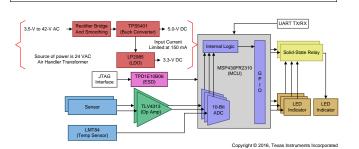
TIDA-01070	Design Folder
MSP430FR2311	Product Folder
LMT84	Product Folder
LP2985	Product Folder
SN74LVC1G27	Product Folder
TPS5401	Product Folder
TPD1E10B06	Product Folder
TLV4313	Product Folder

Features

- Airflow Differential Based System Alerts
- Temperature Sub-Threshold Condenser Cutoff Relay
- Fan Override Run Relay
- Uses Existing HVAC Power Supply
- 10¹⁵ Write Cycle Endurance Ferroelectric RAM (FRAM)
- Sensor Signal Filter Bypass
- ESD Protection
- JTAG Programming Interface With GPIO Access
 Pins

Applications

- Building Automation
- HVAC System Controller
- Filter Replacement Management
- HVAC Efficiency Monitoring



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1 System Overview

1.1 System Description

HVAC systems have a strong dependency on airflow. This airflow controls not only the efficiency of the system, but the behavior of the system as well. Filter replacement is therefore an integral maintenance action that dictates airflow characteristics in the system.

As the air filter becomes dirty, there is reduced airflow through the return plenum, putting unnecessary strain on the AC system. Typical solutions for this problem include filter changing reminders based on a predetermined length in days, or analyses of system run time for a cooling cycle. While these are somewhat effective, they do not address the rudimentary issue of airflow efficiency, which is a better indicator of when a filter change is necessary.

This TI Design for preventative and predictive maintenance monitors the temperature of the evaporator coil as well as the differential airflow from the filter to the air handler blower. The results help determine if there is adequate airflow across the evaporator coil or significant reduction in airflow through the filter.

In the event of a coil freeze resulting in a lack of heat transfer from the air to the evaporator, the system triggers a solid-state 24-V relay that shuts off the condenser, disallowing more refrigerant to be pushed into the expansion valve. A secondary relay ensures the blower fan continues to push ambient air across the coil to accelerate the temperature increase into acceptable operation range, while indication to the user a problem with the systems airflow.

For airflow monitoring, two piezoelectric vibration sensors are used in conjunction with a charge amplification and rectification filter and MCU to determine the airflow differential between the locations of each sensor. This gives the possibility of extracting system issues based on fluctuations in the differential during a typical cooling cycle.

1.2	Key	System	Specifications
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PARAMETER		SPECIFICATIONS			
Target application	HVAC, Building Automation,	HVAC, Building Automation, Airflow Monitoring			
Input voltage	3.5- to 30.0-V AC	3.5- to 30.0-V AC			
Temperature sensing accuracy	± 0.4°C typical	± 0.4°C typical			
On state surrent consumption	MIN	TYP	MAX		
On-state current consumption	7.33 mA	10.70 mA	14.08 mA		
Operating temperature	-40°C to 85°C	-40°C to 85°C			
MCU operating frequency	16 MHz (max)	16 MHz (max)			
Sensor sample rate	500 kHz maximum at V_{cc} =	500 kHz maximum at V_{CC} = 3 V			
System wake-up time	10 µs	10 µs			
Sensor filtering bandwidth	1 MHz	1 MHz			

Table 1. Key System Specifications



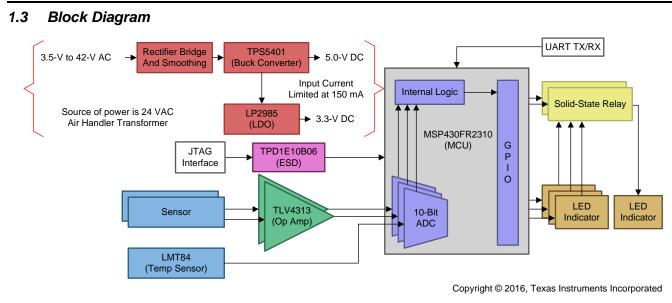


Figure 1. Block Diagram

1.4 Highlighted Products

Key features for selecting the devices for this reference design are highlighted in the following subsections. Find the complete details of the highlighted devices in their respective product datasheets.

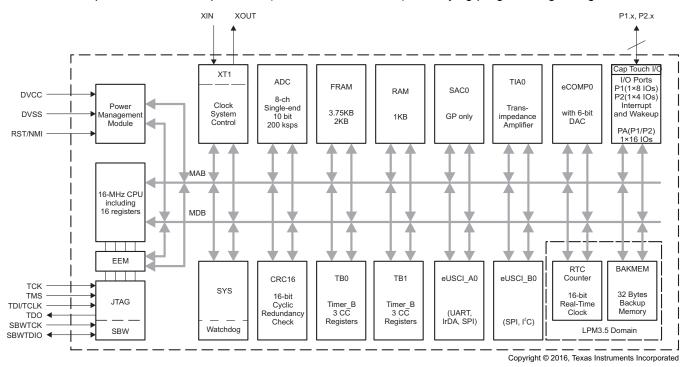
1.4.1 MSP430FR2311

The ultra-low-power MSP430FR2311 FRAM microcontroller (MCU) features embedded non-volatile FRAM and different sets of peripherals targeted for various sensing and measurement applications. The architecture, FRAM, and peripherals, combined with extensive low-power modes, are optimized to achieve extended battery life in portable and wireless sensing applications. FRAM is a new non-volatile memory that combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash, all at lower total power consumption.

The MSP430FR2311 FRAM MCU is the world's first MCU with a configurable low-leakage current sense amplifier and features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) also allows the device to wake up from low-power modes to active mode typically in less than 10 μ s. Additionally, developers can reduce PCB real estate by up to 75 percent with integrated analog, EEPROM, crystal, and MCU functionality in a 4-mmx3.5-mm package. The feature set of this microcontroller is ideal for applications ranging from smoke detectors to portable health and fitness accessories

In the TIDA-01070, the MSP430FR2311 runs the mathematical algorithms used to compare peripheral sensor data from the airflow sensors as well as the temperature sensor inside the air handler. This device was chosen for the following reasons:

- 8-channel 10-bit ADC
- Low-power FRAM
- Multiple communication protocols (I²C, SPI, SBW, UART) for varying programming configurations







1.4.2 LMT84

The LMT84/LMT84-Q1 is an analog output temperature sensor. The temperature sensing element is comprised of a simple base emitter junction that is forward biased by a current source. The temperature sensing element is then buffered by an amplifier and provided to the OUT pin. The amplifier has a simple push-pull output stage, thus providing a low impedance output source.

In the TIDA-01070, the LMT84LP is used for high-accuracy, low-power temperature sensing. The 1.5-V board mounted IC measures ambient internal air handler temperature at the evaporator coil with an accuracy of $\pm 0.4^{\circ}$ C.

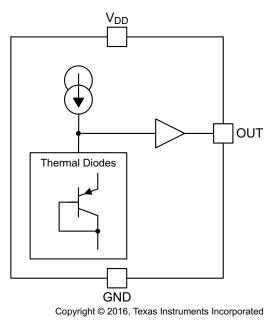


Figure 3. LMT84LMP Block Diagram

1.4.3 LP2985-3.3

The LP2985 fixed-output, low-dropout regulator offers exceptional, cost-effective performance for both portable and non-portable applications. The LP2985 is capable of delivering a 150-mA continuous load current. Standard regulator features such as overcurrent and over-temperature protection are included.

Features:

- Ultra-low dropout, typically 280 mV at full load of 150 mA
- Wide V_{IN} range: 16 V max
- Low I_Q : 850 μ A at full load at 150 mA
- Shutdown current: 0.01 µA typ
- Low noise: 30 μV_{RMS} with a 10-nF bypass capacitor
- Stable with low-ESR capacitors, including ceramic
- Overcurrent and thermal protection
- High peak-current capability



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1.4.4 SN74LVC1G27

The SN74LVC1G27 device performs the Boolean function $Y = \overline{A + B + C}$ or $Y = \overline{A \times B \times C}$ in positive logic. NanoFree[™] package technology is a major breakthrough in IC packaging concepts, using the die as the package.

This device is fully specified for partial-power-down applications using I_{OFF}. The I_{OFF} circuitry disables the outputs, preventing damaging current backflow through the device when it is powered down

In the TIDA-01070 application, this logic gate is used to indicate an acceptable system status. If there are no issues detected, all inputs will be driven low, producing a high output for the system ok LED.

Features:

- Available in the Texas Instruments NanoFree ٠
- Supports 5-V V_{cc} operation
- Inputs accept voltages up to 5.5 V
- Supports down translation to V_{CC}
- Max t_{pd} of 4.5 ns at 3.3 V
- Low power consumption, 10-µA max ICC
- ±24-mA output drive at 3.3 V

1.4.5 **TPD1E10B06**

The TPD1E10B06 device is a single-channel electrostatic discharge (ESD) transient voltage suppression (TVS) diode in a small 0402 package. This TVS protection product offers ±30-kV contact ESD, ±30-kV IEC air-gap protection, and has an ESD clamp circuit with a back-to-back TVS diode for bipolar or bidirectional signal support. The 12-pF line capacitance of this ESD protection diode is suitable for a wide range of applications supporting data rates up to 400 Mbps. The 0402 package is an industry standard and is convenient for component placement in space-saving applications. Typical applications of this ESD protection product are circuit protection for audio lines (microphone, earphone, and speakerphone), SD interfacing, keypad or other buttons, VBUS pin and ID pin of USB and general-purpose I/O ports.

In the TIDA-01070 design, the TPD1E10B06 is used for ESD protection at the JTAG interface of the circuit board.

1.4.6 **TLV4313**

The TLVx313 family of operational amplifiers are general-purpose, low-cost devices that are ideal for a wide range of portable applications. Rail-to-rail input and output swings, low guiescent current, and wide dynamic range make the op amps well-suited for driving sampling analog-to-digital converters (ADCs) as well as other single-supply applications.

The robust design of the TLVx313 devices provides ease-of-use to the circuit designer: unity-gain stability with capacitive loads of up to 150 pF, integrated RF/EMI rejection filter, no phase reversal in overdrive conditions, and high electrostatic discharge (ESD) protection (4-kV HBM). The devices are optimized for operation at voltages as low as 1.8 V (±0.9 V) and up to 5.5 V (±2.75 V), and are specified over the extended temperature range of -40°C to 125°C.

Features:

- Precision amplifier for cost-sensitive systems
- Low Io: 65 µA/ch
- Wide supply range: 1.8 to 5.5 V
- Low noise: 26 nV/√Hz at 1 kHz
- Gain bandwidth: 1 MHz
- Rail-to-rail input/output
- Low input bias current: 1 pA
- Low offset voltage: 0.75 mV
- Unity-gain stable



- Internal RF/EMI filter
- Extended temperature range: -40°C to 125°C

1.4.7 TPS5401

The TPS5401 device is a 42-V, 0.5-A, step-down regulator with an integrated high-side MOSFET. Currentmode control provides simple external compensation and flexible component selection. A low-ripple pulseskip mode reduces the supply current to 116 μ A when outputting regulated voltage with no load. Using the enable pin, shutdown supply current is reduced to 1.3 μ A when the enable pin is low. Undervoltage lockout (UVLO) is internally set at 2.5 V, but can be increased using the enable pin. The output voltage start-up ramp is controlled by the slow-start pin that can also be configured for sequencing or tracking. An open-drain power-good signal indicates the output is within 94% to 107% of its nominal voltage.

A wide switching-frequency range allows efficiency and external component size optimization. Frequency foldback and thermal shutdown protect the part during an overload condition.

Features:

- 3.5- to 42-V input voltage range
- 200-m Ω high-side MOSFET
- High efficiency at light loads with a pulse-skipping Eco-mode[™] control scheme
- 116-µA operating quiescent current
- 1.3-µA shutdown current
- 100-kHz to 2.5-MHz switching frequency
- Synchronizes to external clock
- Adjustable slow start and sequencing
- UV and OV Power-Good output
- Adjustable UVLO voltage and hysteresis
- 0.8-V ±3.5% internal voltage reference

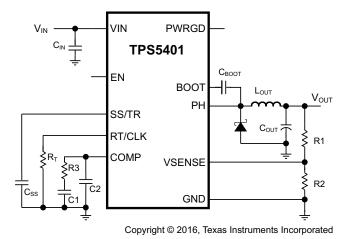


Figure 4. TPS5401 Block Diagram

1.5 System Design Theory

To develop a predictive or preventative HVAC coil airflow device, it is necessary to have a firm understanding of the A/C cycle as well as the potential methods for detecting issues in the system based on variations from cycle to cycle. The ensuing sections outline the theory used to develop and design the TIDA-01070.



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System Overview

1.5.1 24-V AC to 5-V DC Power Supply Design

The TIDA-01070 requires a 3.3-V power supply to operate. By taking advantage of the proximity to the air handler's 120-V AC to 24-V AC transformer, rectification and smoothing can be integrated into the system to provide the required 3.3 V at 150 mA, along with a 5.0-V power rail for peripheral devices added at a later time. The 24-V AC transformer output, once fully rectified, has a peak DC voltage of 34 V, calculated from Equation 1:

$$V_{PDC} = \sqrt{2} \times V_{AC} - 2 \times V_{F}$$

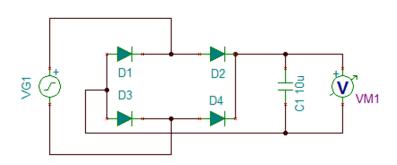


Figure 5. TINA-TI Bridge Rectifier Model

Figure 5 represents the first stage of the power signal conditioning chain, rectification and smoothing. Diodes 1-4 are contained in the DF02S-E3/77 bridge rectifier. This particular device has an operating voltage of 200 V at 1 A, well within the operating conditions of the 24-V AC transformer. The $10-\mu$ F ceramic capacitor is added to smooth the signal output of the rectifier bridge, whose value is determined from Equation 2. Figure 6 shows the resulting transient analysis of the circuit. The analog signal is worst case amplitude for the transformer, and the DC signal is the output of VM1 in Figure 5.

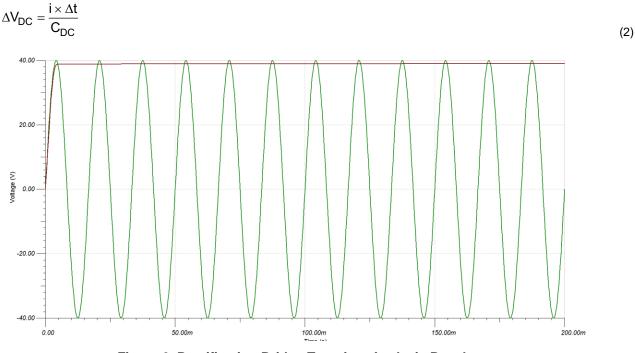


Figure 6. Rectification Bridge Transient Analysis Results

Once the 24-V AC supply voltage is rectified and smoothed, the voltage needs to be significantly reduced in order to provide the correct supply level to the circuitry. As shown in Figure 7, the TPS5401 Buck Converter is used in conjunction with various passive components in order to provide the 5-V, 150-mA target values. These values were fine-tuned and optimized using the WEBENCH online power design program.

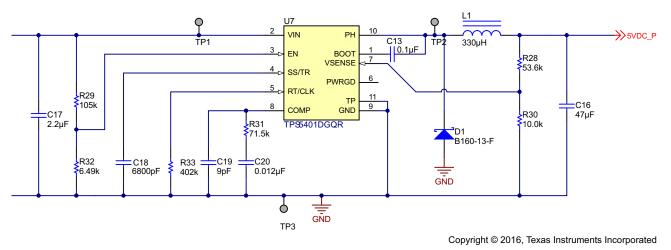


Figure 7. TPS5401 Buck Converter Circuit

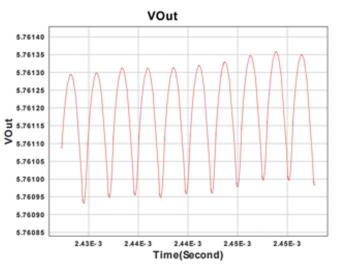


Figure 8. Power System Steady-State Output Voltage Plot

As can be seen from Figure 8, there is less than a $40-\mu V$ ripple in the output of the TPS5401. The switching frequency of the signal is measured to be approximately 392 kHz with a total output power rating of 0.75 W. These values can be found in the following table along with other analysis data, verifying both the robustness and efficiency of the design.

NAME	VALUE	CATEGORY	DESCRIPTION	
Cin IRMS	0.047268315	Current	Input capacitor RMS ripple current	
Cin Pd	1.56E-05	Power	Input capacitor power dissipation	
Cout IRMS	0.012864999	Current	Output capacitor RMS ripple current	
Cout Pd	6.14E-07	Power	Output capacitor power dissipation	
Cross Freq	9004.651439	Op_Point	Bode plot crossover frequency	
D1 Tj	39.59713778	Op_Point	D1 junction temperature	
Diode Pd	0.053615295	Power	Diode power dissipation	
Duty Cycle	12.75920452	Op_Point	Duty cycle	
Efficiency	78.692	Op_Point	Steady-state efficiency	
Frequency	392338.7399	General	Switching frequency	
Gain Marg	-26.00373808	Op_Point	Bode plot gain margin	
IC lpk	0.172282831	Current	Peak switch current in IC	
IC Pd	0.112329231	Power	IC power dissipation	
IC Tj	37.63838771	Op_Point	IC junction temperature	
ICThetaJA	68	Op_Point	IC junction-to-ambient thermal resistance	
lin Avg	0.022693	Current	Average input current	
IOUT_OP	0.15	Op_Point	I _{OUT} operating point	
L Ipp	0.044565662	Current	Peak-to-peak inductor ripple current	
L Pd	0.037125	Power	Inductor power dissipation	
Low Freq Gain	78.97869453	Op_Point	Gain at 10 Hz	
Mode	ССМ	General	Conduction mode	
Phase Marg	65.7309317	Op_Point	Bode plot phase margin	
Pout	0.75	General	Total output power	
Total Pd	0.203087826	Power	Total power dissipation	
VIN_OP	42	Op_Point	V _{IN} operating point	
Vout Actual	5.088000076	General	V _{OUT} actual calculated based on select voltage divider resistors	
Vout OP	5	Op_Point	Operational output voltage	
Vout p-p	3.87E-04	Op_Point	Peak-to-peak output ripple voltage	
Vout Tolerance	1.702560193	General	V _{OUT} tolerance based on IC tolerance load) and voltage divider resistors it applicable	

Table 2. Power Subsystem Steady State Analysis Results

1.5.2 HVAC Application Theory

The following HVAC principles are the basis for the design of this particular system. They are used for optimum placement of sensors, in addition to how the software should analyze the incoming data from the sensors.

1.5.2.1 Airflow Dynamics

Airflow dynamics are different in every system, but there are a few aspects of the airflow that hold true for all systems. When the air handler is running, there are two areas of differing pressure within the system. These are the low pressure side, induced in the return air cavity by the suction of the blower fan, and the high pressure side, leading into the supply plenum and air vents. Figure 9 shows these areas within the setup environment used for testing. The pressure in the return cavity will be proportional to the airflow access through the filter with the addition of peripheral airflow through non-airtight points within the system housing neglecting turbulence.



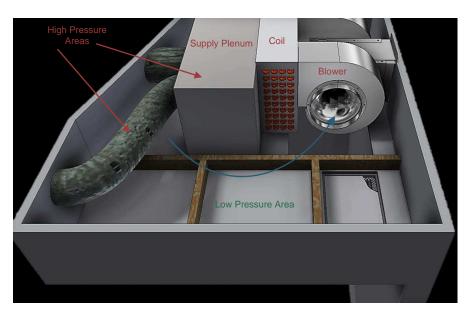


Figure 9. Airflow Analysis Environment

During normal off cycle conditions for the system, the pressure will be equalized between the internal system housing pressure, shown in Figure 10 in yellow, and the ambient room pressure shown in red. This causes an initial backflow of air into the return space from the supply as well as through the filter and non-airtight areas of the system to equalize the two pressures.

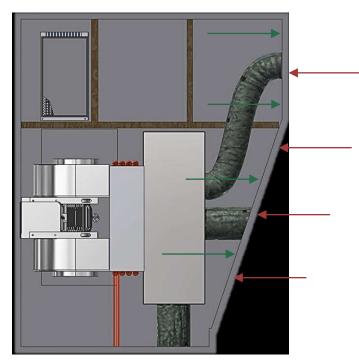


Figure 10. Top View of Testing Environment



System Overview

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When the filter airflow becomes restricted, there is a reduction in pressure at the return air, creating more suction in the return section of the system. This will result in higher air intake from the peripheral air sources of the system due to the pressure differential increase between the two, and the restriction at the air filter. The blower motor will also increase in RPM due to the decreased load caused by the airflow restriction, which can be detected by a vibration sensor mounted carefully on the blower or motor housing. This restriction at the air filter will cause the vibrational difference to become reduced, as the vibration picked up at the filter is now vibration from the motor alone, with no airflow influence.

1.5.2.2 Evaporators and Metering Devices

The evaporator coil is at the heart of the cooling cycle in most HVAC systems. The evaporator coil is responsible from removing heat from the air traveling through the air handler at any point in time while the system is in an active cooling cycle. As airflow velocity changes, so does the heat transfer characteristics of the HVAC system.

Another major component dictating the temperature of the evaporator is a metering device. There are two main metering devices used in residential HVAC systems to regulate the flow of refrigerant into the evaporator coil. This includes a piston, located in the line set going into the evaporator, as well as the thermostatic expansion valve (TXV). The TXV includes a bulb and capillary tube that is placed in contact with the suction line of the evaporator coil, and insulated from the ambient air to reduce refrigerant throttling error. The gas inside the bulb expands and contracts with the temperature of the suction line, controlling the flow of refrigerant into the low pressure side of the evaporator. The piston simply regulates the flow by a fixed size orifice to the low pressure side. The smaller opening of this orifice only allows a small amount of refrigerant through creating a large pressure differential between the two sides, but does not regulate refrigerant flow based on suction line temperature.

Once the refrigerant enters the expansion valve, the change in pressure allows the refrigerant to decrease in temperature drastically. For an R-22 system, the refrigerant after the expansion valve is approximately 75% liquid and 25% vapor at 70 psig and 41°F. Conversely, the refrigerant entering the orifice is approximately 278 psig at 105°F. For R410A systems, this is 130 psig at 45°F and 390 psig at 115°F. As the air is pulled across the fins of the evaporator by the blower fan, the heat is absorbed by the evaporator, allowing the remaining liquid refrigerant to boil off into a vapor around 40°F or 4.44°C. This system behavior, and conversely a change in the thermal characteristics of the system can indicate airflow issues. Including a temperature sensor in close proximity of the evaporator coil allows the difference between the exiting refrigerant temperature and the target temperature mentioned above to be monitored.

1.5.2.3 Detecting System Airflow Changes

The properties associated with refrigerants and their respective pressure at any given time dictate the temperature characteristics of the system. These characteristics can be used to monitor airflow conditions as well as prevent system damage due to improper filter changing frequency. Additionally, piezoelectric sensors can be used to correlate temperature data with the airflow through the system through differential vibration data analysis.

Ideally, the temperature differential between the expansion valve input to the evaporator and the suction line output from the evaporator should be around 10°F, dependent also on factors related to the condensing unit. When there are airflow issues across the evaporator coil, the temperature differential becomes less due to a lack of heat being absorbed by the refrigerant. This results in residual liquid refrigerant exiting the evaporator, unable to transition to vapor. In relation to velocity issues, the faster air moves across the fins, the less time there is for heat transfer between the two. Conversely, if airflow is too slow across the evaporator, the air will become colder due to the increased contact time with the fins.

This reduction in airflow velocity can be detected by monitoring the temperature of the evaporator coil as well as the vibration differential from the outside of the filter to the blower. As previously mentioned, if there is not adequate airflow across the fins of the coil, it can potentially freeze into a block of ice. This can be prevented by enforcing a temperature threshold system cutout relay. Additionally, a lower differential between the piezoelectric sensors may be used to indicate poor airflow through the filter, indicating a filter change is needed. The following simulations are used to demonstrate the behavior of the design based on environmental conditions within the air handler.



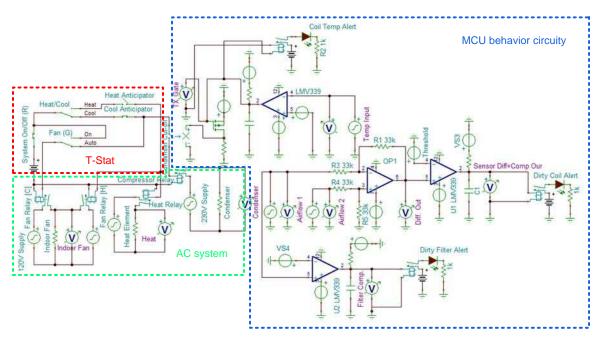


Figure 11. Complete System Integration Test Circuit

Figure 11 was developed through TINA-TI to demonstrate the behavior of this device when integrated into an existing A/C system. The system contains three main sections: the thermostat, the HVAC system equipment, and the MCU behavior replication circuitry. The following output images represent the MCU output based on environmental factors of the system during sensor polling.

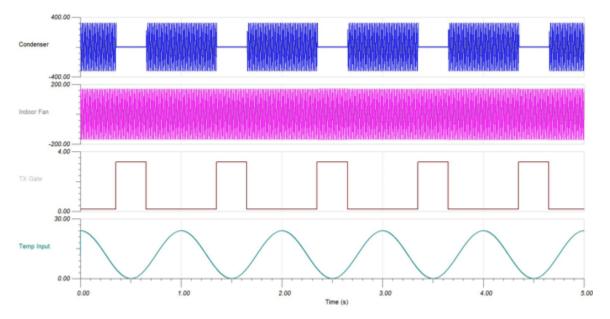


Figure 12. Sub-Threshold Compressor Shutdown Plot

Figure 12 shows the simulation for sub-temperature threshold condenser cutoff relays. The temperature input is represented by a sinusoidal signal, mimicking the change in temperature during and after a cycle. As can be seen from the plots, once the temperature falls below a certain value, the MCU sends a logic high output to the solid-state relay SR latch, shutting the condenser off while leaving the indoor blower fan running to decrease thaw time.

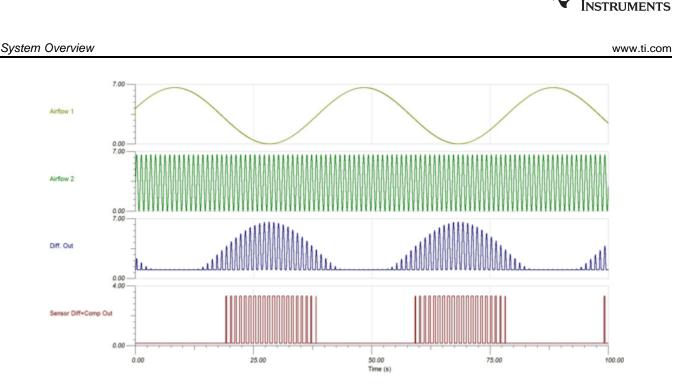


Figure 13. Piezoelectric Sensor Differential-Based Indicator Plot

Figure 13 shows the system behavior with respect to piezoelectric sensor integration. The top two signals represent the vibration signals of the sensors placed at the filter and blower motor, respectively. As the differential between these two vibration sensors increases, shown in blue, the LED indicator is triggered, also providing an input signal for peripheral low power components if desired.

1.5.3 Piezoelectric Vibration Sensor Theory

The word piezo comes from the Greek word piezein, meaning to press or squeeze. Piezoelectricity refers to the generation of electricity or of electric polarity in dielectric crystals when subjected to mechanical stress and, conversely, the generation of stress in such crystals in response to an applied voltage. In 1880, the Curie brothers found that quartz changed its dimensions when subjected to an electrical field and generated electrical charge when pressure was applied. Since that time, researchers have found piezoelectric properties in hundreds of ceramic and plastic materials. Many piezoelectric materials also show electrical effects due to temperature changes and radiation. This reference design is limited to piezoelectricity. More detailed information on particular sensors can be found by contacting the manufacturer.

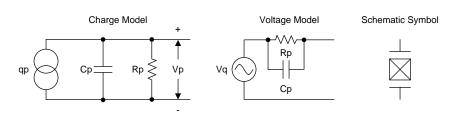
1.5.3.1 Theory and Modeling

The basic theory behind piezoelectricity is based on the electrical dipole. At the molecular level, the structure of piezoelectric material is typically an ionic bonded crystal. At rest, the dipoles formed by the positive and negative ions cancel each other due to the symmetry of the crystal structure, and an electric field is not observed. When stressed, the crystal deforms, symmetry is lost, and a net dipole moment is created. This dipole moment forms an electric field across the crystal.

In this manner, the materials generate an electrical charge that is proportional to the pressure applied. If a reciprocating force is applied, an AC voltage is seen across the terminals of the device. Piezoelectric sensors are not suited for static or DC applications because the electrical charge produced decays with time due to the internal impedance of the sensor and the input impedance of the signal conditioning circuits. However, they are well suited for dynamic or AC applications.

A piezoelectric sensor is modeled as a charge source with a shunt capacitor and resistor, or as a voltage source with a series capacitor and resistor. These models are shown in Figure 14 along with a typical schematic symbol. The charge produced depends on the piezoelectric constant of the device. The capacitance is determined by the area, the width, and the dielectric constant of the material. As previously mentioned, the resistance accounts for the dissipation of static charge.

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Figure 14. Piezoelectric Sensor Models

Taking advantage of the aforementioned effects of a clogged filter on the system, piezoelectric sensors can be placed outside the filter and in close proximity to the blower motor to monitor the differences in airflow between the two locations. Due to the decrease in air flowing across the filter when dirty, the difference between the vibration values of the filter sensor and the blower motor sensor will decrease.

1.5.3.2 Sensor Signal Conditioning Design Theory

Normal output voltages from piezoelectric sensors can vary from microvolts to hundreds of volts, and signal conditioning circuitry requirements vary substantially. Key items to consider when designing the amplifier are:

- Frequency of operation
- Signal amplitude
- Input impedance
- Mode of operation

The following model assumes that the sensor output needs a moderate amount of amplification, and that the desired signal levels are in the 3- to 5-V range for full scale. Typically, the high impedance of the sensor requires an amplifier with high-input impedance.

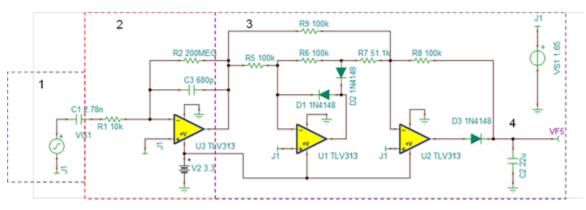


Figure 15. Piezoelectric Charge Amplifier and Rectification Circuit

1.5.3.2.1 Sensor Modeling (Section 1 in Figure 15)

A piezoelectric sensor can be modeled as a voltage source in series with a capacitance. C1 is equal to the parallel plate capacitance found on the sensor's datasheet and will vary from sensor to sensor. The designer needs to take this value into consideration when designing the charge amplifier section.

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Charge Amplification (Section 2 in Figure 15) 1.5.3.2.2

For this stage,

$$V_{OUT} = -\left(\frac{C1}{C3}\right) \times V_{IN}$$

The output voltage is proportional to the charge generated on the plates of C1, and the voltage gain is set by the ratio of C1 to the feedback capacitor C3. Different sensors will have varying capacitance. In addition, different airflow environments will result in different charge generated by deflection. Therefore, it may be necessary to adjust the feedback capacitor value to tune this stage's gain depending on the expected signal amplitude. Based on initial testing, expected input signal levels are between 50 to 300 mV. In our case $V_{cc} = 3.3$ V, and the output is centered on $V_{cc}/2$, so this TI Design can have a 1.65-V swing before clipping the signal. This design has a gain of 4, a maximum swing of 1.2 V or 2.4 V peak to peak, which fits into the desired range with some overhead left over. As charge is generated on C1 (the sensor), it will transfer to C3 and begin to build there. Without R2, this would quickly lead to the capacitor fully charging and the amplifier would drift into saturation. R2 slowly bleeds the charge off of the capacitor to prevent this. The combination of C3 and R2 in the feedback network also creates a high-pass filter on the incoming signal. The corner frequency of this filter must be set very low since this design is working with low frequencies. The last thing to consider is that R2 will provide a DC bias path for the input bias current, and will create an offset of

$$V_{OFFSET} = I_{bias} \times R_2$$

(4)

(5)

This is why it is important to choose an op amp with a very low input bias current.

1.5.3.2.3 Absolute Value Circuit and Smoothing (Sections 3 and 4 in Figure 15)

For the absolute value stage of the piezoelectric signal conditioning circuit:

$$V_{OUT} = |V_{IN}|$$
 (Unity Gain)

Because the goal is to produce a quasi-DC signal from the input, the first step will be rectification. This is an "absolute value" circuit, which does full-wave rectification of the input signal to produce an output that is all greater than the offset voltage. See the transient analysis in Figure 16 for an example of the output at this stage. The resistors used for R5 through R9 should be 1% tolerance to leave the gain unaffected, as well as to ensure that both the positive and negative inputs are rectified equally. If R9 and R6 differ in value, this will be seen on the output as every other peak being lower than the others. Small tolerance resistors help maintain symmetry. The output diode and capacitor serve to smooth the output and provide as close to a DC signal as possible for reading by the ADC. However, the actual output will not be as smooth as the simulations show due to the sporadic nature of the input signal.





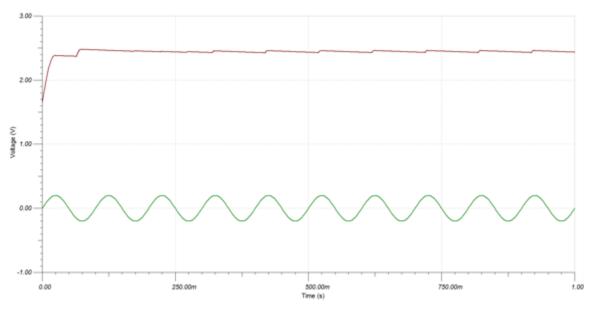


Figure 16. Input Signal versus Output Signal Transient Analysis

1.5.4 MCU and Logic Gate Application Theory

The MCU MSP430FR2311 is used for the analysis of data as well as for the control of peripheral devices used in conjunction with the TIDA-01070. This device also includes FRAM, which allows for infinite write cycles for ADC data, as well as byte and word access capabilities. The onboard 10-bit ADC is used for the peripheral sensors, 2-piezoelectric vibration sensors and the LMT84 temperature sensor. Although piezoelectric sensors are used in this specific design, the GPIO interface allows the user to integrate various other sensors specific to their needs.

The SN74LVC1G27 three-input NOR gate is used for reduced internal software and more efficient GPIO pin use as well. This gate is used with the following signals as inputs:

- SSR relay logic out
- Dirty coil logic out
- Dirty filter logic out

As stated previously, the NOR gate implements the Boolean function:

 $Y = \bar{A} \times \bar{B} \times \bar{C}$

(6)

17

When there are no issues detected in the system, all three input signals will be at a logic 0, which will drive the output of the NOR gate to a logic high. This value is then fed to a System OK LED to inform the user that no airflow issues are currently detected within the proximity of the evaporator coil.

1.5.5 Software Development Theory

For the software development of the TIDA-01070, the logic and analysis procedures on ADC data deployed onto the MCU are the result of varying simulation conditions to find a correlation between the differences in piezoelectric sensor data from each case and the temperature sensor located on the board. The combination of the piezoelectric sensors and the temperature monitoring sensor creates a software system that bases airflow issues on mutually supporting system data. Therefore, the system should never freeze without the user first alerted to an airflow issue because they are directly related, assuming there are no refrigerant level issues. The following subsections represent the logic deployed to the MSP430[™] for sensor analysis and system response.





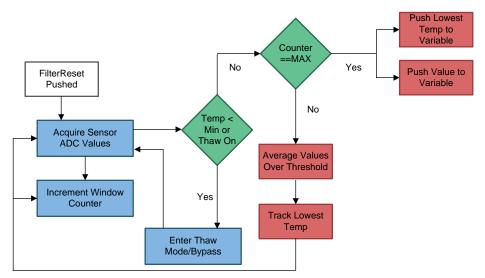


Figure 17. Initial Threshold Value Acquisition Logic

Figure 17 represents the logic implemented the first time the board is run, as well as when the filter is replaced to account for system degradation over time. Once the filter reset button is pressed, the next full window cycle average and minimum temperature is used as comparison values for the remainder of cycles occurring until the next button press occurs. The values are then decreased slightly and placed into a separate threshold variable to allow for slight performance degradation before indicating an issue with the system. After this initial logic sequence, the system can enter the main routine as shown in Figure 18.





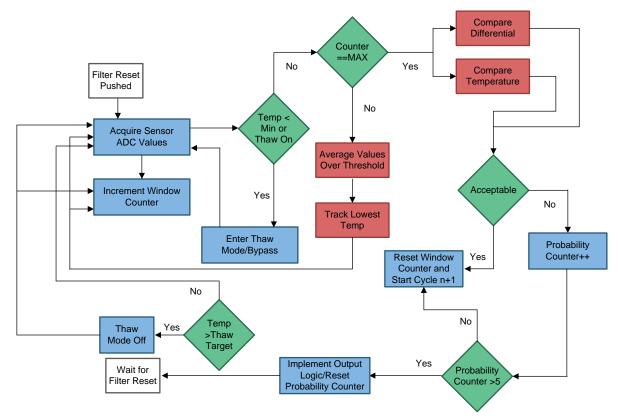


Figure 18. Main Software Logic

The main system loop for the MCU is relatively similar to the initialization logic flow for the first few elements. The main difference occurs with the comparison of window averages versus pushing comparison values into memory for later use. In this logic, the values acquired in the main cycle window are compared to a value slightly lower than that stored in memory for initialization conditions. In this case, both averages are compared with this value. If the value is within limits, the cycle continues in normal operation. If either is below the designated value, a probability based sub-process is initiated to predict the likelihood of the indicated system issue. After a predetermined number of occurrences within a specified cycle limit, the system event is considered to be verified based on frequency of occurrence, and the user is alerted of the specific issue. As with the previous logic cycle for initial value acquisition, the temperature based thaw mode is also included for the main cycle as a safety precaution. This thaw mode is disabled once the evaporator coil temperature reaches a suitable operating temperature, also alerting the home owner of the issue. The system then runs normally until the next detected issue occurs.



2 Getting Started Hardware and Software

This section outlines the information for getting the board up and running as fast as possible. Take care when moving jumper pins to avoid possible damage to the components. Ensure all pin placements are correct before supplying power to the board.

2.1 Board Overview

For ease of use, all main components, headers, and test points are located on the top side of the board, as shown in Figure 19. The main power section of the board is located in the bottom left corner of the board, allowing for easy access and quick wiring into existing 24-V AC supplies. The power jumper is located to the left of the power system along with the power testing points and 5-V supply pins. Also along the left edge of the board are the external piezoelectric sensor connection headers. The bypass jumper pins directly behind the headers allow for a 1.65- or 0-V bias voltage selection, as well as a complete filtering section bypass jumper for raw data feeds into the ADC. Both filtering sections are located in clusters on the upper left side of the board. The right side of the board is the access point for the JTAG interface for MCU programming, as well as GPIO access for peripheral device control, such as a solid-state relay. There are two buttons located on the board, one for MCU reset, and another for threshold value calibration. The addition of booster pack headers for the CC2650 gives the design the capability for wireless BLE communication with nearby mobile devices. The board also includes four LEDs of different color for system alerts.

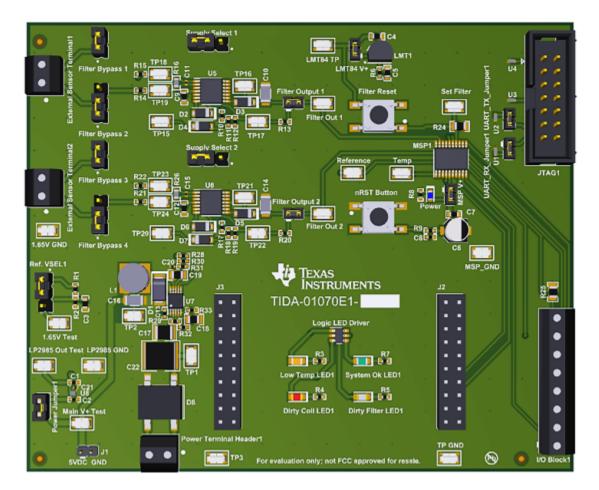


Figure 19. TIDA-01070 Board View

2.2 Getting Started With Hardware

In order to replicate the circuit used to test the TIDA-01070, set the headers in the orientation described in Table 3. Connect the HVAC system load last to power the board.

HEADER	CONNECTION
Power Jumper Short	Short
Ref. VSEL1	Short Pins 1 and 2
Filter Bypass 1	Short
Filter Bypass 2	Short Pins 1 and 2
Filter Bypass 3	Short
Filter Bypass 4	Short Pins 1 and 2
Supply Select 1	Short Pins 2 and 3
Supply Select 2	Short Pins 2 and 3
Filter Output 1	Short
Filter Output 2	Short
MSP V+	Short
LMT84 V+	Short
UART_TX_Jumper1	Short
UART_RX_Jumper1	Short
Power Terminal	24-V AC
External Sensor 1	Piezoelectric Sensor 1
External Sensor 2	Piezoelectric Sensor 2

Once the jumper positions are verified with respect to Table 3, the rectification circuitry will provide the voltage to the DC power supply, which will enable the onboard circuit components. The MSP430 initially will wait for the Filter Reset pushbutton to be pressed before taking sensor data. It is important to integrate the sensors and place the device in the desired location before pushing this button to prevent erroneous threshold values from being set for the system.

Once the Reset Filter button is pressed, the system waits for a logic high signal on pin 8 of the I/O Block 1 Header to begin taking data for the threshold values. Once the system threshold values are obtained, the device will continually poll the HVAC system as dictated in Section 1.5.5. Once the "System On" signal goes low again, the MSP430 stops polling until the next cycle.

The System On signal is a 3V3 logic signal that is designed to come from a solid-state relay such as the TIDA-00751, in which a 3V3 logic signal is used in conjunction with an SR latch to activate a solid-state relay. These are also the recommended devices for the peripheral relays used to shut down the condenser and run the fan. Find more information on the TIDA-00751 here.



2.3 Loading Firmware

This firmware was developed using TI's Code Composer Studio™ (CCS) software (version 6.1.3) and MSP430Ware (version 3.50.00.04), which was downloaded from the CCS App Center.

The TI Design hardware is programmed by connecting the MSP430FR2311 LaunchPad's JTAG emulator from J101 to the TI Design JTAG1 header. Another emulator can be used, but the authors have only tested with the MSP430FR2311 LaunchPad. On the MSP430FR2311 LaunchPad, remove all jumpers from J101. This will disconnect the JTAG emulator from LaunchPad's onboard the MSP430. Use shunt wires to make the following connections:

- LaunchPad's SBWTCK to TI Design's JTAG1 header, pin 7 •
- LaunchPad's SBWTDIO to TI Design's JTAG1 header, pin 1
- LaunchPad's GND to TI Design's JTAG1 header, pin 9

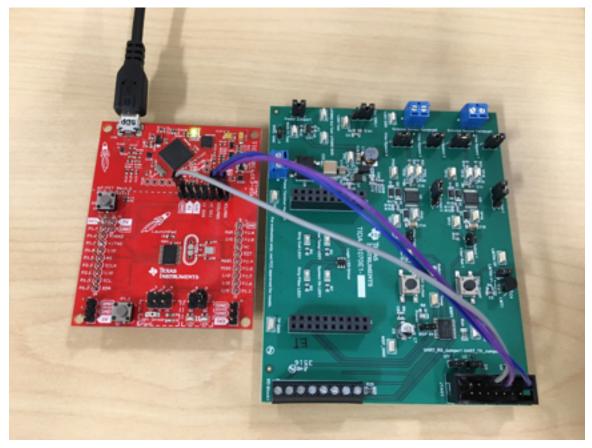


Figure 20. Connection of MSP430FR2311 LaunchPad and TI Designs Hardware for Programming and Debugging



Using a micro USB, connect the LaunchPad to the laptop, which will turn on the LaunchPad's green LED (LED101). After setting up all the hardware, follow these steps to load the firmware on the TI Design using CCS:

- 1. If not done already, import TIDA-01070 Firmware into CCS:
 - (a) Click on the Project drop-down menu, and then "Import CCS Projects...".
 - (b) Click on the "Select archive file" radio button.
 - (c) Click the "Browse..." button
 - (d) Navigate to the location where TIDA01070_Firmware.zip is located and click "Open".
 - (e) Under Discovered projects, make sure TIDA01070_Firmware is checked.
 - (f) Click the "Finish" button to import the CCS project.
- 2. In Project Explorer, select TIDA01070_Firmware and make it the active project.
- 3. Click on the green bug icon to connect to the MSP430FR2311 device.

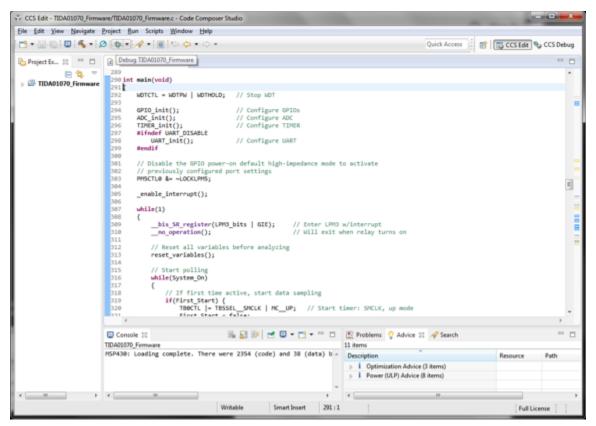


Figure 21. CCS Green Bug Icon



Getting Started Hardware and Software

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4. After clicking on the green bug icon, CCS will automatically build and load the firmware.

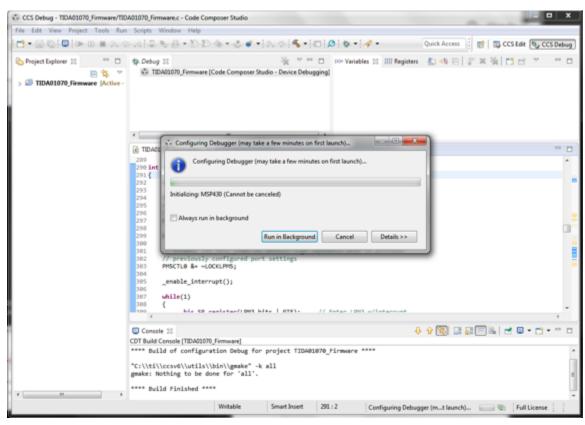


Figure 22. CCS Loading Firmware Onto TI Design



5. Upon successful firmware load, the PC cursor should be pointing at the main function.

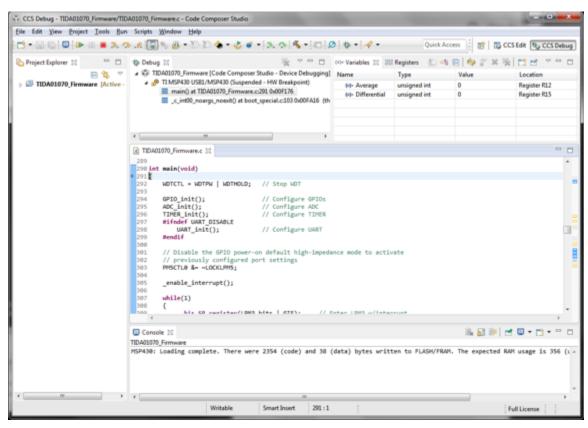


Figure 23. Successful Firmware Loading Using CCS



6. Click on the red square to terminate the connection.

CCS Debug - TIDA01070_Firmware/TID	A01070_Firmware.c - Code Co	mposer Studio	-		-			x
Eile Edit Yiew Project Iools Bun	Scripts Window Help							
	x 🛛 🔊 🖉 🖓 🔊 x) 🌢 = 🕹 💰 = 🔊	· • • • • • •	ð 🕸 • 🛷 •	Quick	Access 🕴 🖬 🗔	CCS Edit 🔊 CCS	Debug
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8 🕹 🔻	 TIDA01070_Firmware TI MSP430 US81/ 			Name	Туре	Value	Location	
Fither TIDA01070_Firmware [Active -		01070_Firmware.c:291.0		00- Average 00- Differential	unsigned int	0	Register R12	
		gs_noexit() at boot_speci		op- Differential	unsigned int	0	Register R15	
	*		,					
	TIDA01070_Firmware.c 3	8						- 0
	289 290 int main(void)							*
	290 Int main(void)							
	292 WDTCTL = WDTP 293	W WDTHOLD; //	Stop WDT					
	294 GPIO_init();	11	Configure GPIOs					
	<pre>295 ADC_init(); 296 TIMER init();</pre>		Configure ADC Configure TIMER					
	297 #ifndef UART		courtgare intex					
	298 UART_init 299 Bendif	0; //	Configure UART					
	209 Bend11 300							
		e GPIO power-on de		nce mode to activ	vate			
	302 // previously 303 PMSCTL0 &= ~L	configured port s OCKLPH5:	ettings					
	304							
	305 _enable_inter 306	rupt();						
	307 while(1)							
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Figure 24. Terminate CCS Emulation Connection

Once the firmware has been loaded, disconnect all wires between the LaunchPad and the TI Design. Follow Section 2.2 for more information on how to setup the hardware for testing.



3 **Testing Setup and Results**

The test setup for the TIDA-01070 consists of two separate testing instances. The first instance, preliminary testing, is used to characterize the HVAC system under optimum operating conditions as well as non-optimum, such as a dirty filter. This data is imperative to the system because the software and sensor placement are based on the ability to diagnose airflow issues through repeatable results.

The second test setup is relatively similar, but is used to test the final design after optimization and fabrication. These procedures can be found in Section 3.4.

3.1 Preliminary Piezoelectric Sensor Testing Setup

In order to characterize the piezoelectric sensors, as well as the difference in LSB based on clean and dirty conditions, the sensors were integrated into a pre-existing system. Figure 25 shows the initial setup of the test environment. The first piezoelectric sensor is placed in the proximity of the filter, outside the scuttle space. The second piezoelectric sensor is placed next to the blower wheel. An MSP430 is placed inside the return air cavity as well, polling the sensors at a rate of 1 kHz. An anemometer is used in addition to the sensors to correlate the piezoelectric data with the actual airflow through the accessible return air filter sections.

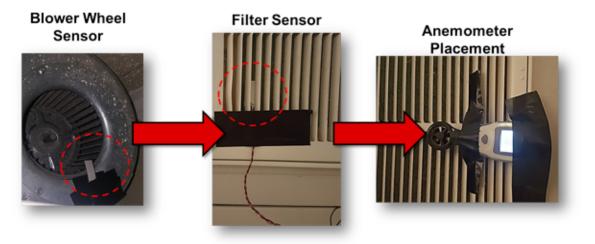


Figure 25. Piezoelectric Sensor and Anemometer Test Setup



Testing Setup and Results

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In order to extract any differences between the piezoelectric sensor differentials with respect to airflow blockage, the tests were implemented with no blockage as well as significant blockage, as shown in Figure 26. This determines specific behaviors unique to either ideal airflow or significant blockage. This test is executed using a sheet of paper to block a majority of the return air grill. The anemometer is placed in a position for accurate readings in each scenario.



Figure 26. Filter Condition Test Setup

Figure 27 represents the logic used for data analysis during the preliminary stages. Each polling interval, the absolute value of the differential between the two piezoelectric sensors is calculated. If the value falls below a predetermined threshold, 70 in this particular case, the sensor data is deemed acceptable and the values are disregarded. If the differential is greater than 70, an internal software counter s incremented and the LSB value is added to the current sum of values over 70. These two values are then used to calculate an updated average as well as displaying through UART to the user for further data analysis.

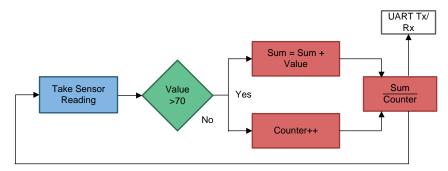


Figure 27. MSP430 Sensor Analysis Logic



3.2 Preliminary Piezoelectric Sensor Test Data

This section analyzes the resulting data from Section 3.1. The rectification circuitry was not used in the preliminary testing due to optimization requirements based on raw input parameters.

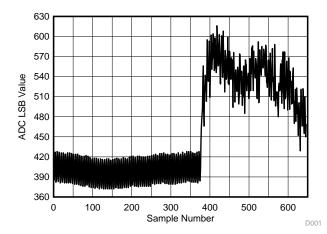


Figure 28. Raw Piezoelectric Sensor Data (System On versus System Off)

Figure 28 shows the piezoelectric sensor data during a typical system startup. As can be seen from the plot, the piezoelectric sensor output oscillates around 400 LSB during the off-phase of the test quite consistently, only deviating slightly at around the 100 to 200 sample range. The off-time section of the plot yields the following parameters shown in Table 4. The sample frequency for this particular dataset was 10 Hz.

PARAMETER	VALUE
Maximum amplitude	475 LSB
Minimum amplitude	372 LSB
Mean LSB value	400 LSB
Median LSB value	399 LSB

Table 4. Off Cycle Plot Analysis Data

Once the system is turned on, there is a distinct discontinuity in the oscillations seen when the system is off. This dynamic can be used as an indicator of when the system starts the next cooling cycle. As can be seen from the right half of Figure 28, once the system is turned on, the oscillations of the piezoelectric sensor become higher in value, but also fluctuate rapidly in amplitude. The on-time section of the plot yields the following parameters shown in .

PARAMETER	VALUE
Maximum amplitude	616 LSB
Minimum amplitude	429 LSB
Mean LSB value	537 LSB
Median LSB value	539 LSB

Table 5. On Cycle Plot Analysis Data



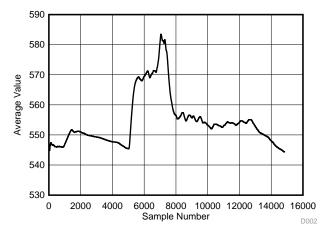


Figure 29. Motor Piezoelectric Sensor Data (Complete Cycle)

Figure 29 represents the data acquired from the second preliminary test. In this test, the sensor was placed on the blower motor housing, attached from the bottom to allow maximum sensitivity to motor vibration. In order to reduce the effects of outlying data points on the analysis, the data points were averaged after each was obtained, acting as a smoothing filter for the plot data. The sample frequency for this dataset is set at 100 Hz.

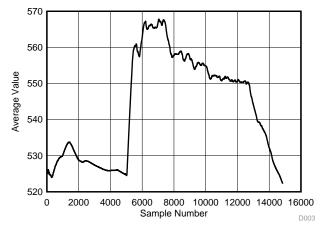
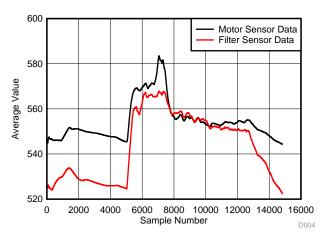


Figure 30. Filter Piezoelectric Sensor Data (Complete Cycle)

Figure 30 shows the ADC data acquired from the filter sensor. This sample set was obtained at the same time as the motor sensor data for comparison between the two under identical conditions, differing only in location. The distinct discontinuity in the plot represents the system being turned on. The plot smoothing is also implemented on this data set to keep consistency between the two. A distinction can be seen from the comparison of the two plots, but their behavior is relatively synchronized as can be seen in Figure 31. The change in amplitude is mainly caused by proximity to the vibration source. This data shows the existence of vibration synchronization between the motor and the filter sensors under normal airflow conditions.









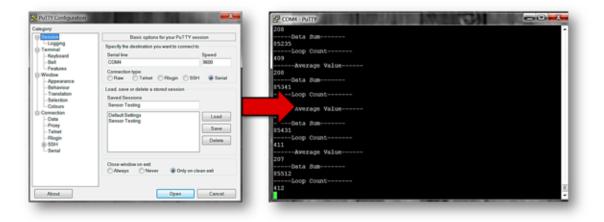


Figure 32. Differential Sensor Data Acquisition Setup

The second test set follows the logic implementation shown in Figure 27. The MCU is connected to a computer through a serial COM port with the use of Putty for UART TX/RX. A baud rate of 115200 is required for this application. Figure 32 shows the setup for the sensor data acquisition as well as the output of the testing. All flowchart variables shown in Figure 27 are labeled accordingly in the UART output for proper analysis.



Testing Setup and Results

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After acquiring the data, the plot shown in Figure 33 represents the findings of test data with respect to both blockage and non-blockage conditions. As can be concluded from the plotted data, there is a significant difference between the plots based on the filter airflow conditions. The anemometer readings can be distinguished based on these two conditions as well. When the filter incurs significant blockage, the differential average between the two locations decreases and has less dynamic plot characteristics than that of the non-blocked filter. In this case, the anemometer readings give an average CFM value of 271.77 ft³/min. When there is no filter blockage the CFM average value jumps to 674.26 ft³/min, almost 3 times that of the blocked filter. This verifies the ability to monitor airflow conditions within the HVAC system using the differential average of the piezoelectric sensors. Table 6 represents some of the extracted statistics from Figure 33.

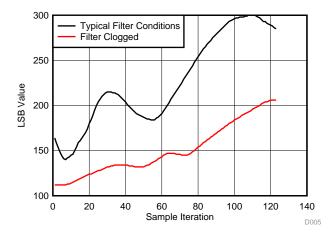


Figure 33. Clean and Dirty Filter Differential Test Data

PARAMETER	BLOCKED RETURN VALUE	NON-BLOCKED RETURN VALUE
Average LSB value	151	227
Maximum LSB value	206	300
Minimum LSB value	112	140



3.3 LMT84 Temperature Sensor Testing Setup and Data

To test the LMT84 temperature sensor, a breadboard and oscilloscope was used with varying temperatures in order to characterize the signal for use in this TI Design. Figure 34 shows the results from the first test. The average value for over 2.5k samples was 925.9 mV for an LSB value of 287. This test was done in the ambient air with no other thermal influence present. Figure 34 shows the LMT84 output waveform for ambient temperature conditions as well as data statistics for the signal.

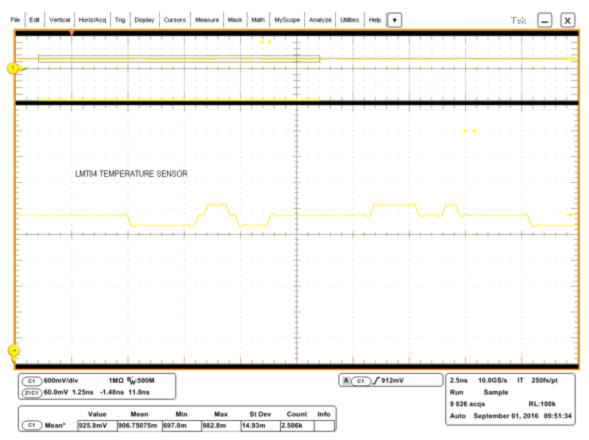


Figure 34. LMT84 Oscilloscope Output Data

Temperature (°C) =
$$\frac{5.506 - \sqrt{(-5.506)^2 + 4 \times 0.00176 \times (870.6 - V_{\text{TEMP}} (\text{mV}))}}{2 \times (0.00176)} + 30$$
(7)

Referring to Equation 7, the voltage and ADC digital output readings can be converted to a temperature value in Celsius. The parabolic equation is an approximation of the transfer table listed in the LMT84 datasheet and the accuracy of the equation degrades slightly at the temperature range extremes. In this particular application, the temperature range will be well within the device limits; therefore, this issue can be disregarded. The MSP430FR2311 has a 10-bit ADC; therefore, the voltage gain per LSB is approximated as Equation 8:

$$\frac{3.3 \text{ v} - 0 \text{ V}}{1024} = 3.22 \frac{\text{mV}}{\text{LSB}}$$

This value can be multiplied by the LSB value from the ADC to find the value of V_{TEMP} in Equation 7. The LSB values acquired from the LMT84 output are higher for lower temperatures and low for higher temperatures.

(8)



Testing Setup and Results

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Figure 35 shows the response of the LMT84 during ambient conditions as well as when exposed momentarily to a heat source. In this test, the values were converted to Celsius as previously described and compared to the temperature reading from a thermocouple temperature probe measuring the temperature of the outer LMT84 package. This test yielded temperature accuracy within $\pm 0.1^{\circ}$ C of the thermocouple reading, with higher accuracy expected in the typical low temperature conditions of this design.

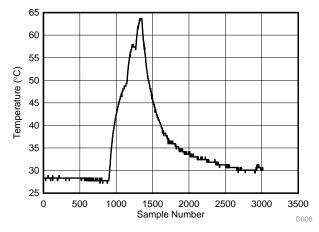


Figure 35. LMT84 Test Data Plot

3.4 Complete System Testing

The final testing of this TI Design involves the integration of all previously mentioned subsystems into the final board. These tests will be analyzed as before, but now factoring in the integration of the subsystems and how well they work as a whole.

PARAMETER	MINIMUM VALUE	TYPICAL VALUE	MAXIMUM VALUE
24-V transformer voltage input	24-V AC	26.77-V AC	30-V AC
Rectification bridge output	34.48 V	—	34.631 V
DC output voltage	—	5.07-V DC	_
LP2985 output voltage	_	3.29-V DC	_
Idle current consumption	_	7.33 mA	—
On-state current consumption	7.33 mA	10.70 mA	14.08 mA
Data TX/RX frequency	1 Hz	20 Hz	150 Hz

Table 7. TIDA-01070 Board Testing Results

Table 7 shows the testing results for the design's power and data transmission rates. A 24-V AC transformer is used as the power supply for the system, wired into the main power supply of the board. The values from the transformer maintained a value slightly over the 24-V expected output, but well within the operating range of this device. This setup is shown in Figure 36.

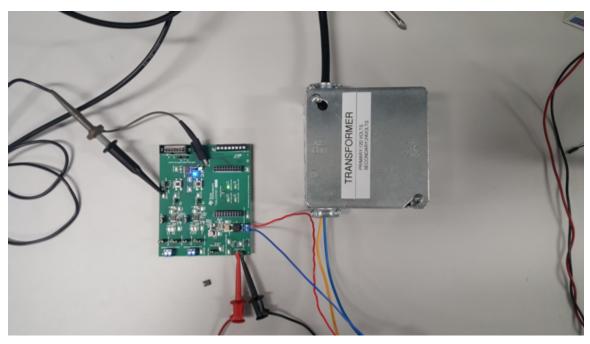


Figure 36. Transformer Connection to Board

As expected, the rectified and smoothed output from the first section of the power conversion chain was over 30 V, reaching a maximum of 34.631 V in 30 minutes of running. After the TPS5401, the voltage is at 5.07 V, very close to the 5.0-V design goal. Finally, after reaching the LDO, the voltage is a constant 3.29 V, only 10 mV from the target value. The blue LED indicates to the user that there is adequate power to the board.



Testing Setup and Results

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Next, the system current consumption was measured by removing the main power supply pins and placing the current probe in series across the jumper terminals, as shown in Figure 37. In order to obtain the best idea of typical current consumption of the device, the device is started without the FRAM loaded, increasing the power consumption of the MSP430FR2311. The Filter set is also pressed during this time to increase the current consumption further for worst case scenarios. As can be seen from the results during operation conditions, the maximum current consumption seen is around 14 mA and the minimum is around 7 mA. This is well below the 150-mA input supply, allowing for higher MCU frequency without the worry of conserving limited current supply.



Figure 37. TIDA-01070 Current Consumption Test Setup

The next test verifies the TINA-TI simulations done for the piezoelectric sensor signal conditioning. Figure 38 shows the setup, which includes a 10-Hz sinusoidal signal applied to sensor input one of the design board. The amplitude is set to 1.65 V_{P-P} .



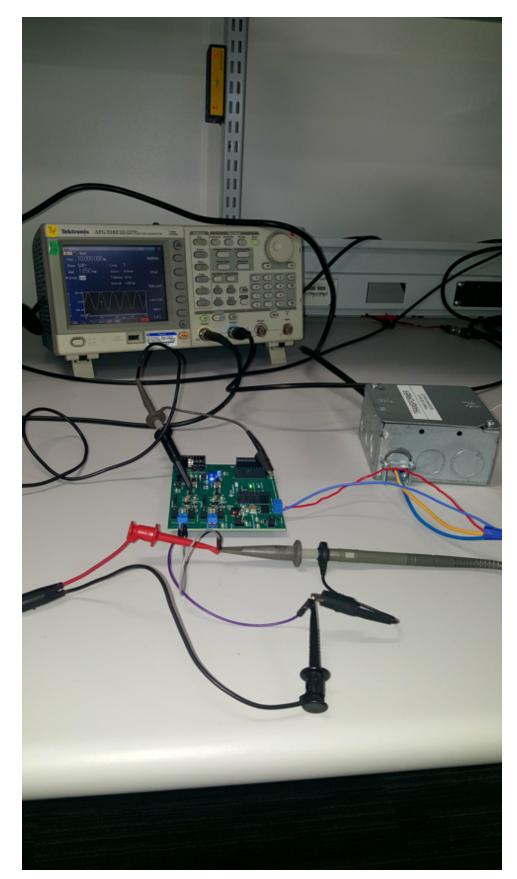


Figure 38. TIDA-01070 Signal Conditioning Test Setup

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Figure 39 represents the output from the signal conditioning circuit of this design. The data replicates that seen in the TINA-TI simulations, confirming the functionality described in Section 1.5.3.

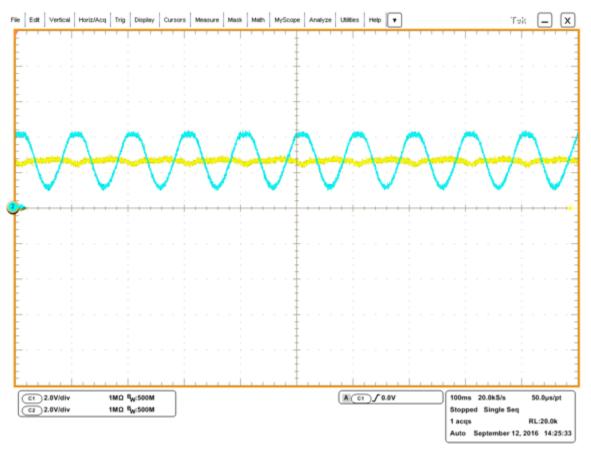


Figure 39. 10-Hz Input Signal versus Signal Conditioning Output

The next test uses the charge and rectification circuitry output for the piezoelectric sensors to acquire the signal differences between that of a clean filter and a dirty filter. For this, implement the software logic mentioned in Section 3.1. The window size is set at 1 for this testing so as to average each value equally with that of the last average. This reduces the smoothing effect of the previous averaging method, allowing for a closer examination of the filter output behavior in true operating conditions. The comparison and temperature threshold have been disabled temporarily to allow for uninterrupted data acquisition.

The voltage reference for the positive input to the first TLV4313 op amp is set at 1.65 V just as in the simulations. The data from this charge rectification circuit is acquired from the output testing point of each respective sensor. The absolute value differential threshold is set for 70 LSB as in the previous test. Due to the dynamic difference between the clean and dirty filter output, a secondary algorithm was implemented in order to acquire the typical value range for dirty filter conditions.

Figure 40 represents the output for this algorithm. The threshold value is started at 70 just as with the clean filter. After 100 samples are taken, if at least half are not above the threshold, the value of the threshold is decremented by 1 LSB and another 100 samples are taken from the sensor. As can be seen from Figure 40, this continues until the first value arrives around a 40 LSB threshold point. The algorithm continues to decrement, slower now, until the value reaches 17 LSB, at which the threshold remains constant. This value is considered the baseline for the dirty filter condition output. From this point, both signals can be acquired for comparison with respect to filter conditions.





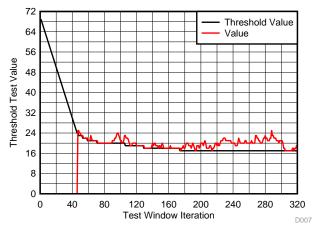


Figure 40. Dirty Filter Threshold Acquisition

Figure 41 represents the absolute valued differential results based on clean and dirty filter conditions. There is a clear distinction from the output LSB range of the clean filter with respect to a dirty one. The next test uses this data in addition to the onboard MSP430 and the LMT84 to ensure an alert is given to the customer in the event of a dirty filter using the conditional behavior acquired in Figure 41. An analysis of this data is also shown in Table 8.

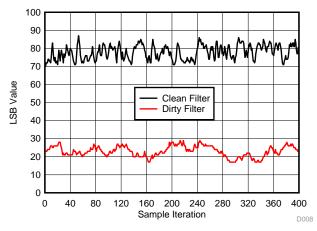


Figure 41. TIDA-01070 Clean and Dirty Filter Output

Table 8.	Clean	and	Dirtv	Filter	Data	Statistics
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PARAMETER	BLOCKED VALUE	NON-BLOCKED VALUE	DIFFERENTIAL
Average LSB value	23	78	55
Max LSB value	29	87	58
Min LSB value	17	70	53



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The clean filter values are over 50 LSB different from the dirty filter values. A closer look at the differential in all three parameters reveals that the values stay within relative proximity of each other with respect to their differences.

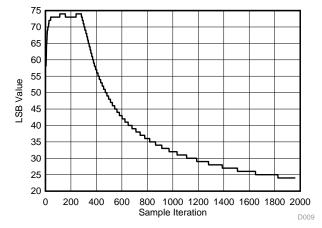


Figure 42. Filter Output From Clean to Dirty

The next test was done to record the actual response of the system when the filter is clean, and then suddenly becomes obstructed or dirty. Figure 42 represents the data taken from the design, using a running average to smooth out the sharp discontinuities in the data. The values stay around 70 to 74 for the first 300 samples. At this point, the return is blocked, simulating a clogged filter, and the average begins to rapidly decrease. As the values get closer to an equilibrium point for the dirty condition, the sample period per LSB can be seen to increase. This test setup is identical to the preliminary piezoelectric testing.



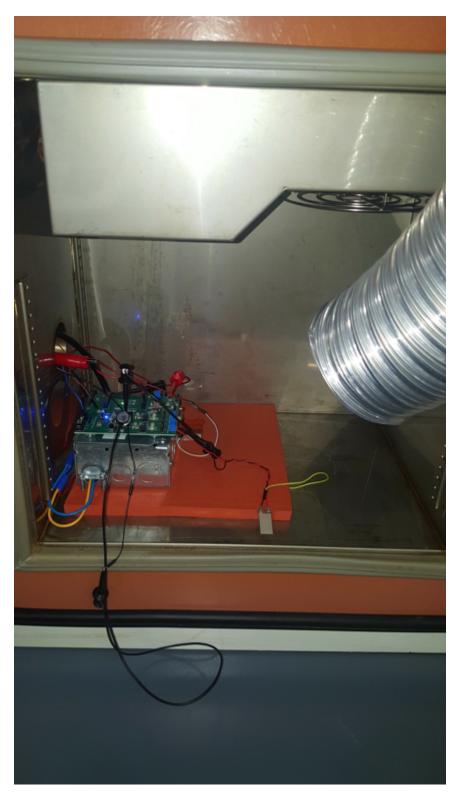


Figure 43. Full Design With Software Testing Setup



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Figure 43 shows the laboratory setup for the final testing of the sensors with the aforementioned software logic deployed to the MSP430FR2311. This test is mainly used to verify the correct functionality of the design logic in addition to ensuring the initial calibration of the device, which allows it to function correctly in multiple environments. An in-line fan is added to a 4-inch dryer vent to provide enough airflow for testing purposes. The temperature testing box is used to simulate the return air space for a typical system. There is also a variation in the piezoelectric sensors to account for how they are to be set up in the system. For this reason, a larger one, shown in the middle of Figure 43, is used in conjunction with a smaller one that is vertically positioned to mimic the mounting position and location on the blower. The outputs of each piezoelectric sensor is monitored on an oscilloscope in addition to the filter dirty signal, which is accessed from the BoosterPack headers for ease of testing.

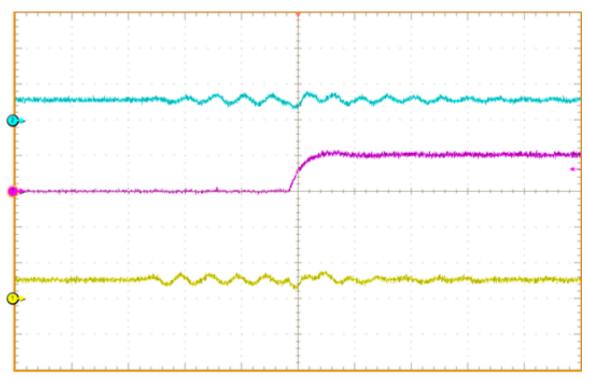


Figure 44. Oscilloscope Signal Output for Dirty Filter

Figure 44 represents the output of the TIDA-01070 design during dirty filter conditions. After starting the inline fan and powering up the board, the Filter Set button is pressed. At this point, 100 samples of data are taken and averaged to find an optimum ideal operation condition based on the current system setup. One these comparison values are obtained, the system goes into polling mode in which samples are taken 20 times per second. Once the value drops below half of that measured during calibration, the probability counter indicates a hit and the variable is incremented by one. If this happens five times consecutively, which equates to 100 samples equal to or below this value, the system determines that there is an airflow issue across the filter and the system stops polling the sensors and alerts the user that there is a potential coil or filter problem. Figure 44 captures the moment the notification of airflow issues occur in the system. At this point of the test, a hand is placed in front of the fan, reducing the piezoelectric vibration until the output is triggered, roughly 5 seconds later.

The final section of the testing is that of the onboard LMT84 temperature sensor. Figure 45 shows the actual recorded temperature from the device compared to the values listed in the datasheet for the LMT84. The accuracy between the two is acceptable, the main difference being the actual 3.3-V supply voltage ranges from board to board.

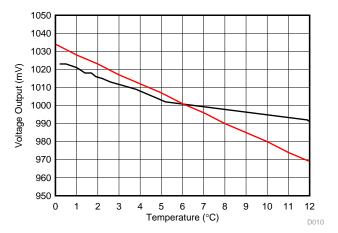


Figure 45. Temperature Variation, Actual versus Referenced



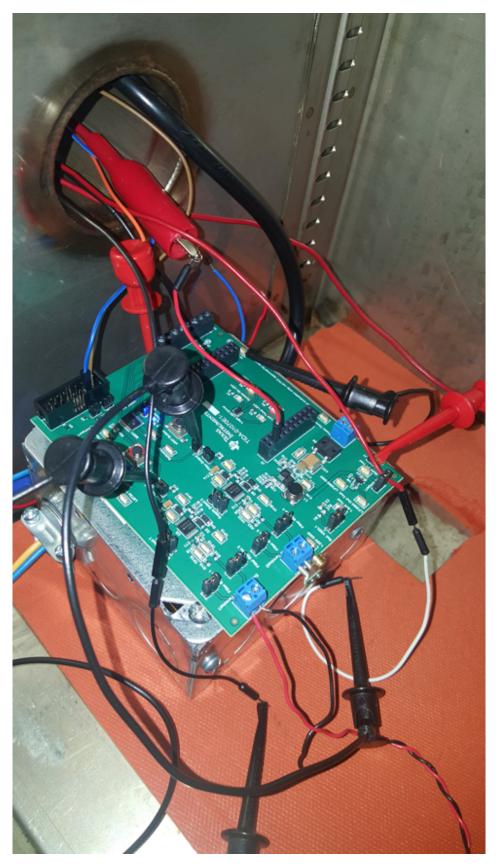


Figure 46. Temperature Threshold and Thaw Temperature Test Setup



After characterizing the LMT84 located on the board, the device was placed in a temperature test environment as seen in Figure 46. This is done to test the logic implemented when the temperature goes below 4°C as well as after the temperature reaches the thaw threshold of 24°C. Once the testing probes are connected and verified to be correct, the temperature box is sealed and the temperature is dropped to 0.2°C. Figure 47 shows the resulting output of the solid-state relay pins once the threshold is reached. As can be seen from the plot, both SSR1 and SSR2 signals go high once the value is reached. At this point, the temperature is the only thing being polled until the system becomes active again after reaching the thaw threshold.

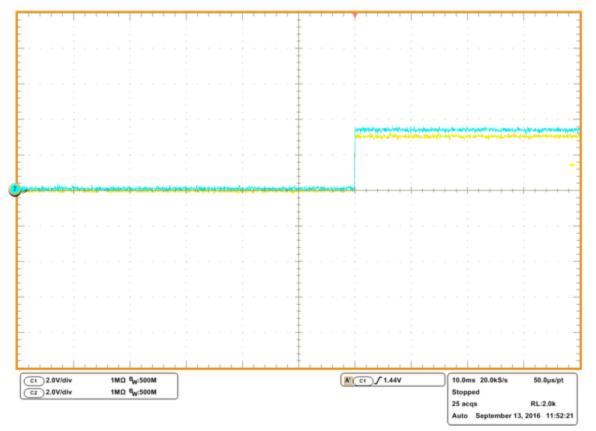


Figure 47. TIDA-01070 SSR1 and SSR2 Oscilloscope Output High



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After the temperature stabilized below 4°C and the SSR output signal was verified to be a constant logic high, the temperature was raised back to the threshold temperature. This is done to verify the logic is correct by resuming the partial sleep mode until the temperature reaches the thaw threshold. Once this temperature is reached, the SSR outputs are dropped to a logic low signal and the system polling continues. Figure 48 shows the SSR signal change once the temperature reaches the target value.

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Figure 48. TIDA-01070 SSR1 and SSR2 Oscilloscope Output Low



4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01070.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01070.

4.3 PCB Layout Recommendations

A careful PCB layout is critical and extremely important in this multiple sensor circuit to provide appropriate device operation and design robustness. As with all mixed signal circuits, pay attention to detail in the layout to save time in troubleshooting later on.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01070.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01070.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01070.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01070.

5 Software Files

To download the software files, see the design files at TIDA-01070.

6 References

- 1. Texas Instruments, WEBENCH® Design Center (http://www.ti.com/webench)
- 2. Texas Instruments, Signal Conditioning Piezoelectric Sensors, Application Report (SLOA033)
- 3. Texas Instruments, Piezoelectric Airflow Sensor Users Guide (TIDU373)
- 4. Texas Instruments, Signal conditioning for piezoelectric sensors, Technical Brief (SLYT369)

7 About the Author

BRIAN DEMPSEY is a systems designer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Brian brings to this role his extensive experience in HVAC systems, along with his experience with mixed signal systems. Brian earned his bachelor of science in electrical engineering (BSEE) from Texas A&M University in College Station, TX. Brian is a member of the Institute of Electrical and Electronics Engineers (IEEE).

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Revision A History

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Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (September 2016) to A Revision					
•	Changed from preview draft		1		

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