

TI Designs: TIDA-010045

IEPE Sensor Analog Front-End With Digital Interface Reference Design



Description

Industrial vibration sensing is a crucial process in condition monitoring, which is necessary for predictive maintenance. An integrated electronic piezoelectric (IEPE) sensor is the most common vibration sensor used in the industrial environment. This design is a simple sensor analog front-end suitable for interfacing the IEPE sensor to an integrated MSP432 ADC converter, allowing a compact implementation for IEPE to IO-Link interface.

Features

- Front-End for Single IEPE Sensor Input
- 14-bit Resolution
- 20-kHz Bandwidth
- Uses MSP432 Integrated ADC
- 4-mA Fixed Current Source Excitation
- ± 6 -V AC Input, 500-k Ω Input Impedance
- Wire-break Detection

Resources

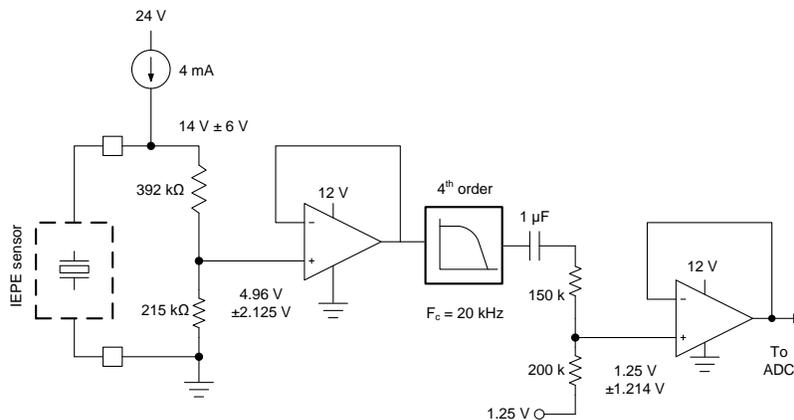
TIDA-010045	Design Folder
TLV431	Product Folder
OPA196	Product Folder
CSD18541F5	Product Folder
OPA4171	Product Folder
TL4050C	Product Folder
TLV760	Product Folder
TPS798-Q1	Product Folder
LMZM23600	Product Folder
INA190	Product Folder
TIOL111	Product Folder
MSP432P401R	Product Folder

Applications

- [PLC Special Function Module/ IEPE](#)
- [PLC Analog Input Module](#)
- IEPE to IO-Link converter



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1 System Description

Predictive maintenance is the ability to predict machine failure early through detection of change in machine health status, collectively known as machine condition. Condition monitoring is essential in the modern industrial environment. The recently-increased interest in condition monitoring demands more affordable, compact condition monitoring circuits that integrate seamlessly within the existing control infrastructure. IEPE vibration sensors are very common in factory floors. More than one monitoring circuit might be attached to a motor or a pump and their readings are to be collected for evaluating the motor or the pump health. This design illustrates compact implementation of an IEPE sensor interface that is connected and powered through a digital IO-Link interface.

1.1 Key System Specifications

This design focuses on footprint and low power rather than performance. An MSP432 microcontroller integrated ADC of 14-bit resolution is used for signal conversion. [Table 1](#) shows a summary of the key system specifications for this design.

Table 1. Key System Specifications

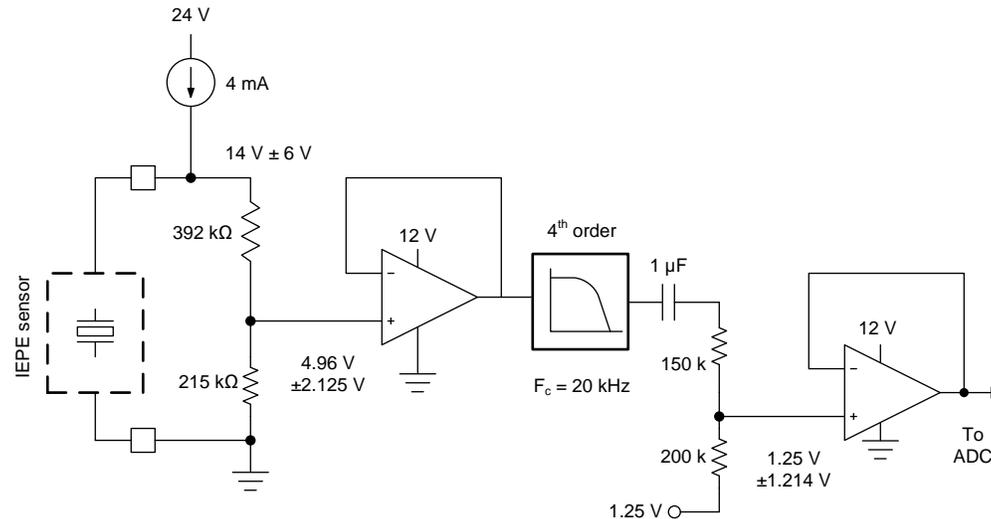
PARAMETER	SPECIFICATIONS
Number of channels	1
Input range	± 6 V
Resolution	14 bits
Bandwidth	0.5 Hz to 20 kHz
Sampling rate	45.454 kHz
SNR	84 dB (signal chain)
Gain	-13.8 dB
Input impedance	610 k Ω
Excitation current	4 mA
Excitation voltage	22 V (minimum)
Operation temperature	-40°C to 85°C
Diagnostic features	wire-break
Form factor	70 mm x 22 mm

2 System Overview

The interface circuit consists of a current source to power the IEPE sensor in addition to an analog chain that scales, filters, and buffers the sensor output signal as shown in Figure 1. Low pass filtering comes first in the chain followed by a high pass filter implemented as a simple RC.

2.1 Block Diagram

Figure 1. TIDA-010045 Block Diagram



2.2 Highlighted Products

2.2.1 TLV431

The TLV431 device is a low-voltage, 3-terminal adjustable voltage reference with specified thermal stability over applicable industrial and commercial temperature ranges. Output voltage can be set to any value between V_{REF} (1.24 V) and 6 V with two external resistors. This device operates from a lower voltage (1.24 V). Active output circuitry provides a very sharp turnon characteristic, making them excellent replacements for low-voltage Zener diodes in many applications, including onboard regulation and adjustable power supplies.

2.2.2 OPA196

The OPAx196 family (OPA196, OPA2196, and OPA4196) is a new generation of 36-V, rail-to-rail e-trim™ operational amplifiers (op amps). These devices offer very low offset voltage ($\pm 25 \mu\text{V}$, typical), drift ($\pm 0.5 \mu\text{V}/^\circ\text{C}$, typical), and low bias current ($\pm 5 \text{ pA}$, typical) combined with very low quiescent current (140 $\mu\text{A}/\text{channel}$, typical) across the entire output range. Unique features, such as differential input-voltage range to the supply rail, high output current ($\pm 65 \text{ mA}$), and high capacitive load drive of up to 1 nF make the OPAx196 a robust, high-performance operational amplifier for high-voltage industrial applications.

2.2.3 CSD18541F5

This 54-m Ω , 60-V, N-Channel FemtoFET™ MOSFET technology is designed and optimized to minimize the footprint in many space constrained industrial load switch applications. This technology is capable of replacing standard small signal MOSFETs while providing a significant reduction in footprint size.

2.2.4 OPA4171

The OPA171, OPA2171, and OPA4171 (OPAx171) are a family of 36-V, single-supply, low-noise operational amplifiers with the ability to operate on supplies ranging from 2.7 V (± 1.35 V) to 36 V (± 18 V). These devices are available in micro-packages and offer low offset, drift, and bandwidth with low quiescent current. The single, dual, and quad versions all have identical specifications for maximum design flexibility.

Unlike most operational amplifiers, which are specified at only one supply voltage, the OPAx171 family is specified from 2.7 to 36 V. Input signals beyond the supply rails do not cause phase reversal. The OPAx171 family is stable with capacitive loads up to 300 pF. The input can operate 100 mV below the negative rail and within 2 V of the top rail during normal operation. These devices can operate with full rail-to-rail input of 100 mV beyond the top rail but with reduced performance within 2 V of the top rail.

2.2.5 TL4050C

The TL4050 series of shunt voltage references are versatile, easy-to-use references suitable for a wide array of applications. The two-terminal, fixed-output device requires no external capacitors for operation and is stable with all capacitive loads. Additionally, the reference offers low dynamic impedance, low noise, and low temperature coefficient to ensure a stable output voltage over a wide range of operating currents and temperatures.

The TL4050 is offered in three initial tolerances, ranging from 0.1% (maximum) for the A grade to 0.5% (maximum) for the C grade. Thus, a great deal of flexibility is offered to designers in choosing the best cost-to-performance ratio for their applications.

With SOT-23-3 and SC-70 packages and requiring a minimum current of 45 μ A (typical), the TL4050 also is ideal for portable applications.

2.2.6 TLV760

The TLV760 is an integrated linear-voltage regulator featuring operation from an input as high as 30 V. The TLV760 has a maximum dropout of 1.2 V at the full 100-mA load across operating temperature. Standard packaging for the TLV760 is the 3-pin SOT-23 package.

The TLV760 is available in 3.3 V, 5 V, 12 V, and 15 V. The SOT-23 packaging of the TLV760 series allows the device to be used in space-constrained applications. The TLV760 is a small size alternative to the LM78Lxx series and similar devices.

The TLV760 is designed to bias digital and analog circuits in applications that are subject to voltage transients and spikes up to 30 V such as appliances and automation applications. The device has robust internal thermal protection, which protects itself from potential damage caused by conditions like short to ground, increases in ambient temperature, high load, or high dropout events.

2.2.7 TPS798-Q1

The TPS798xx-Q1 is the first device in a line of 50-V, high-voltage micropower low-dropout (LDO) linear regulators. This device is capable of supplying 50-mA output current with a dropout voltage of only 300 mV. Designed for low quiescent current, high voltage (50-V) applications, 40 μ A operating and 1 μ A in shutdown makes the TPS798xx-Q1 an ideal choice for battery-powered or high-voltage systems. Quiescent current is also well-controlled in dropout.

Other features of the TPS798xx-Q1 include the ability to operate with low equivalent series resistance (ESR) ceramic output capacitors. This device is stable with only 1 μ F on the output. Most older devices require from 10- μ F to 100- μ F tantalum capacitors for stability. Small ceramic capacitors can be used without the necessary addition of ESR, as is common with other regulators. Internal protection circuitry includes reverse input-battery protection, reverse output current protection, current limiting, and thermal limiting to protect the device in various fault conditions.

2.2.8 LMZM23600

The LMZM23600 integrated-inductor power module is specifically designed for space-constrained industrial applications. This device is available in two fixed output voltage options of 5 V and 3.3 V, and an adjustable (ADJ) output voltage option supporting a 2.5-V to 15-V range. The LMZM23600 has an input voltage range of 4 V to 36 V and can deliver up to 500-mA of output current. This power module is extremely easy to use, requiring only 2 external components for a 5-V or 3.3-V output design. All aspects of the LMZM23600 are optimized for performance driven and low EMI industrial applications with space-constrained needs. An open-drain, Power-Good output provides a true indication of the system status and negates the requirement for an additional supervisory component, saving cost and board space. Seamless transition between PWM and PFM modes along with a no-load supply current of only 28 μ A ensures high efficiency and superior transient response for the entire load-current range. For easy output current scaling, the LMZM23600 is pin-to-pin compatible with the 1000-mA output current capable LMZM23601.

2.3 System Design Theory

For detailed information about IEPE sensors, their performance specification, and interface design see the [IEPE Vibration Sensor Interface for PLC Analog Input Reference Design](#).

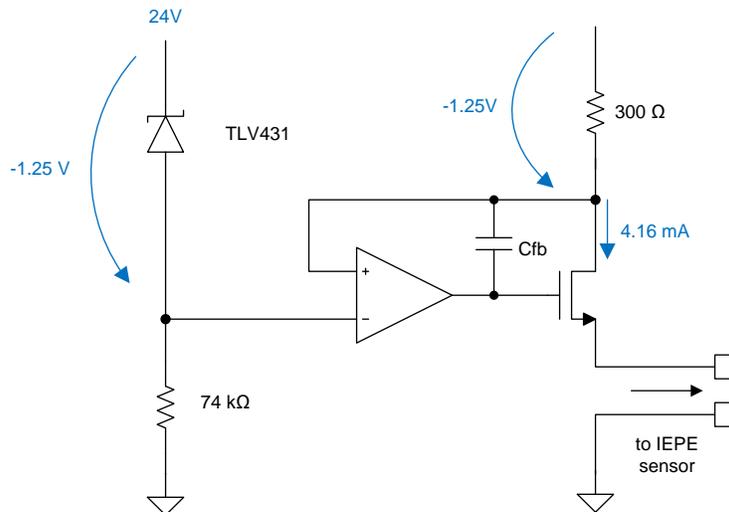
2.3.1 Circuit Design

2.3.1.1 Current Source

The current source shown in [Figure 2](#) relies on the shunt regulator TLV431 used as an accurate voltage reference which is copied to the output branch through an op-amp buffer. The buffer is placed with the output transistor in a loop to ensure high output impedance of the current source.

The TLV431, when used as a reference, keeps an accurate 1.25 V between its terminals. The current in this branch can be controlled through a resistor. 74 k Ω is used to reduce the current to about 0.3 mA.

Figure 2. Current Source Schematic



The op-amp buffer ensures the output voltage is equal to the input voltage, which places 1.25-V over the accurate 300- Ω resistor, resulting in approximately 4-mA current in the output branch. The output transistor in the feedback loop is used to provide high output impedance for the current source.

Feedback resistor Cfb is required to maintain amplifier stability by reducing its bandwidth.

2.3.1.2 Input Buffer

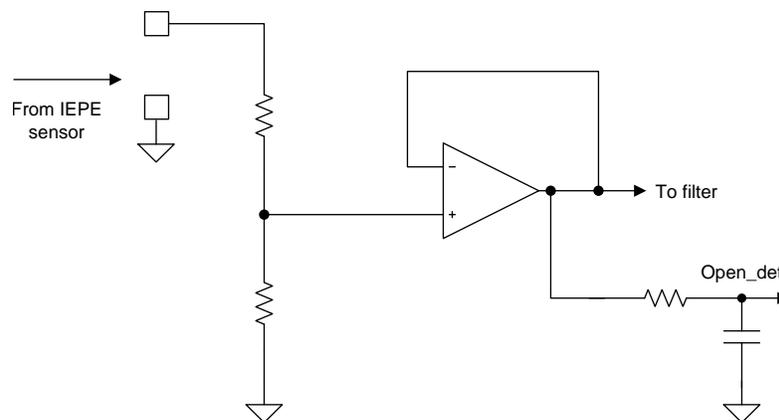
The IEPE vibration sensor output signal has a DC of 8 V to 14 V, in addition to an AC signal of 6 V at its peak, which translates to an input signal span of 2 V to 18 V. In case of a wire break, the input voltage is pulled up through the current source close to a 24-V level.

Input signal is scaled down using an accurate resistive potential divider by a factor of 0.4 as shown in [Figure 3](#). This translates the 24 V into 9.6 V maximum, with the normal input at 14-V DC translated to 5.6 V. The potential divider has an input impedance of 500 k Ω .

An op-amp unity gain buffer is used to drive the filter in the next stage and to isolate the potential divider from filter input impedance to ensure accurate scaling.

A simple RC filter following the input buffer is used to detect open circuit (broken wire), by monitoring when input signal DC level exceeds the typical expected value. The open_det signal is sent to one ADC input in MSP432.

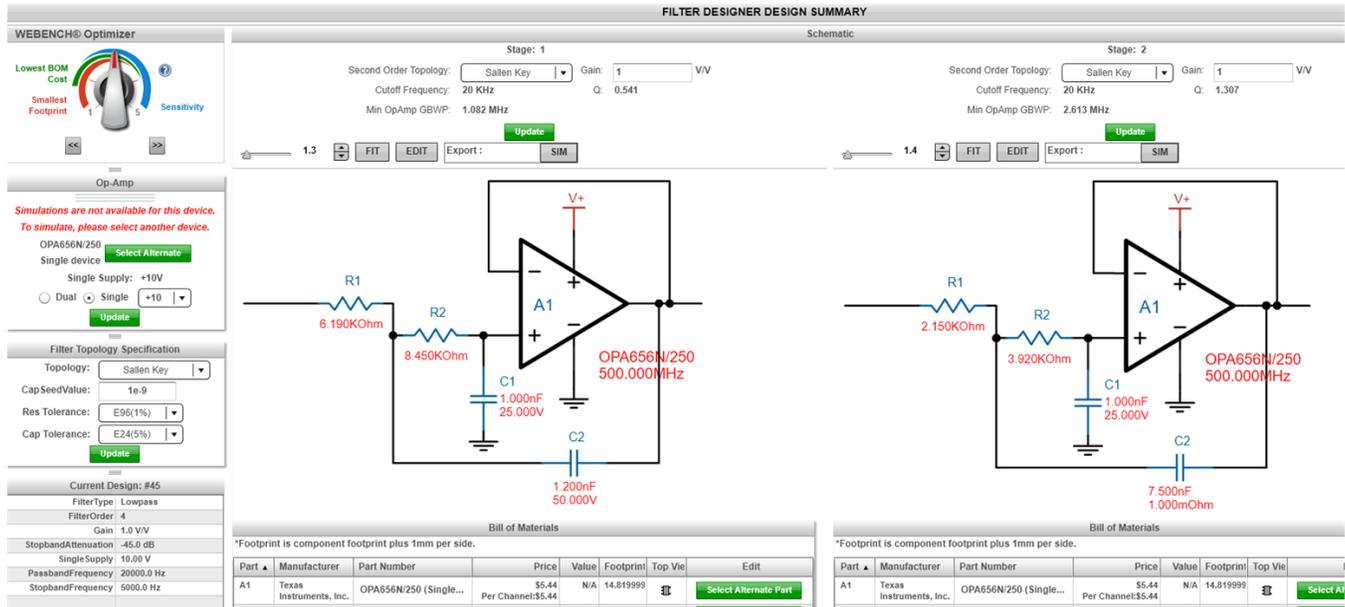
Figure 3. Input Buffer



2.3.1.3 Low Pass Filter

A 4th-order, 20-kHz bandwidth Butterworth low pass filter is designed using WEBENCH® Filter Designer and implemented using a two-stage Sallen-Key topology. Figure 4 shows the WEBENCH output for given filter requirements. The low input impedance of the filter dictates the use of the input buffer.

Figure 4. Filter Design in WEBENCH®



2.3.1.4 High Pass Filter and ADC Driver

Output signal from the low pass filter will still carry a scaled level of DC. This DC must be removed to use the full ADC input range for AC signal and achieve the maximum dynamic range.

A simple, high-pass filter composed of CR filter is attached to the output of the filter stage. Further scaling is done to bring the signal level within the ADC input range. Moreover, the common-mode is set to 1.25 V which is half of the value of the ADC common-mode.

With the integrated MSP432 ADC input not very high, impedance requires a low impedance driver. An op-amp buffer using the OPA4171 is used.

2.3.1.5 Common-Mode Voltage Reference

The shunt regulator TL4050C25, which has a 2.5-V output, is used to generate both the V_REF as the reference voltage at 2.5 V for the integrated ADC and the common-mode voltage V_CM at 1.25 V for the ADC input signal.

2.3.1.6 Power Stage

The very compact module LMZM23600 is set to produce 15 V from a 24-V input (input voltage can vary from 18 V to 36 V). The TPS79801 step-down converter generates 12 V out of the 15 V. The 12-V rail is used to power the op amps used in the signal chain, while the 24-V input is used to power the current source directly.

The 12-V input is further converted down to 3.3 V using the TLV76033 regulator for powering the integrated ADC within the MSP432.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

Figure 5 shows the hardware for this design. Table 2 describes the usage of each jumper on board.

Figure 5. TIDA-010045 Board

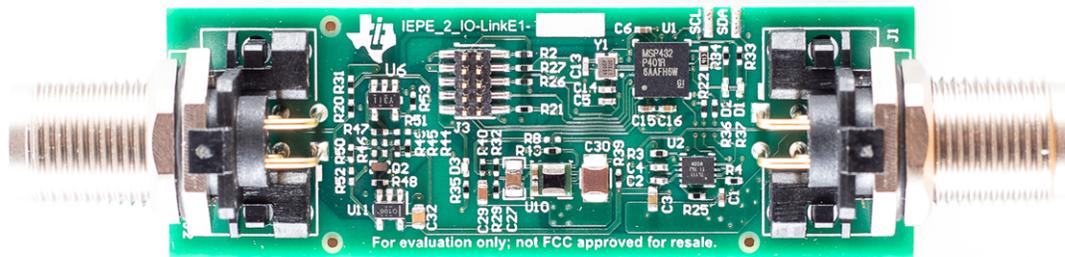


Table 2. Jumpers

JUMPER OR CONNECTOR	DESCRIPTION
J1	IO-Link connector, 4-pin M12 male connector
J2	Sensor connector, 4-pin M12 male connector, only 2 pins (1-GND, 3-signal) are connected to the board
J3	JTAG programming and debugging connector

3.1.2 Software

No special software is required for testing. Any generic IO-Link master can be used to transfer the sampled data to the PC. The data frame can be programmed over IO-Link for an up to 1k sample size, and output mode can be programmed to raw time domain samples or data points after FFT operation.

TMG USB IO-Link Master V2 – EMC is used to transfer the IO-Link stream to USB, while a custom program was used to collect data sent over USB and store it for further evaluation.

3.2 Testing and Results

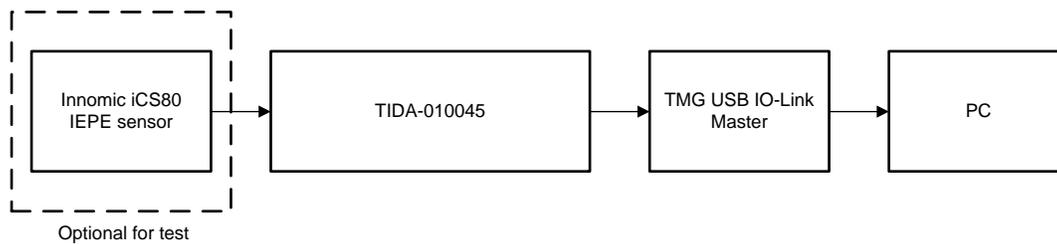
3.2.1 Test Setup

Figure 6 shows the test setup for validating this design. The Innomic iCS80 IEPE sensor can be connected to this design for vibration input testing. For mere resolution and SNR testing, the sensor is not required. A simple resistive load or IEPE emulator is connected.

The TMG USB IO-Link Master is attached to the TIDA-010045 IO-Link port and bridges the IO-Link transfer into normal USB transfer read by a PC and stored in text files for further processing.

The 1024 raw time data samples are collected and processed using scilab.

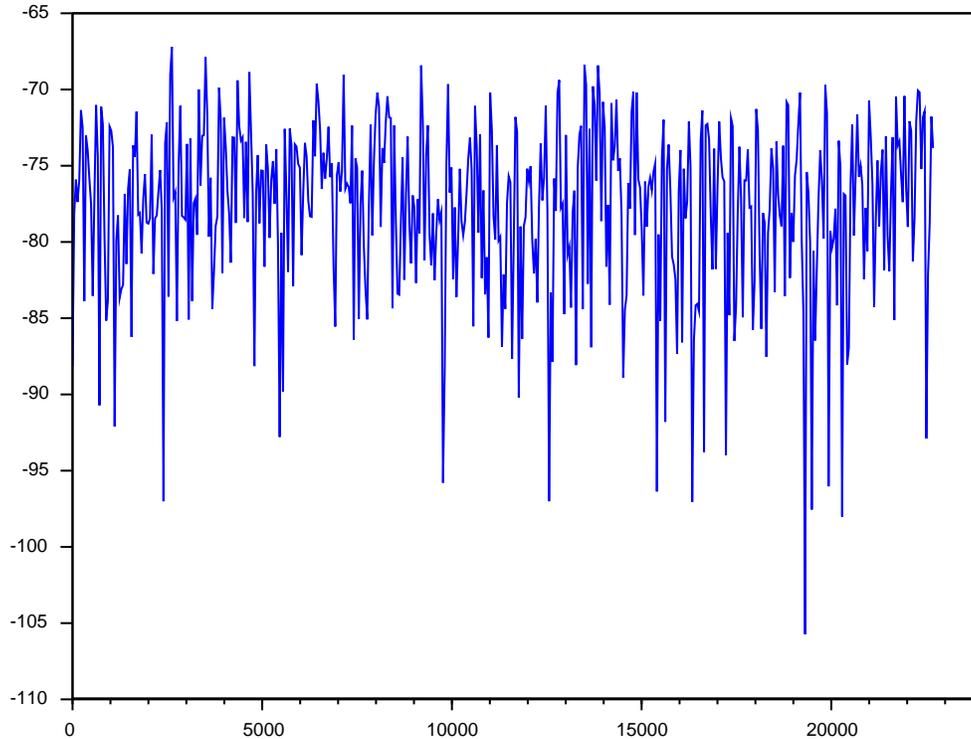
Figure 6. Test Setup



3.2.2 Test Results

A data set of 1024 is extracted, and FFT with Hann window is applied on it. The FFT of the data is shown in Figure 7. Average noise floor is -77 dB, which is attributed to test noisy environments.

Figure 7. FFT of 1024 Data Points



4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-010045](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-010045](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-010045](#).

4.4 Altium Project

To download the Altium Designer® project files, see the design files at [TIDA-010045](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-010045](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-010045](#).

5 Related Documentation

1. Texas Instruments, [IEPE Vibration Sensor Interface Reference Design for PLC Analog Input](#)

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