Designing a front-end interface for vibration sensors that monitor machine health

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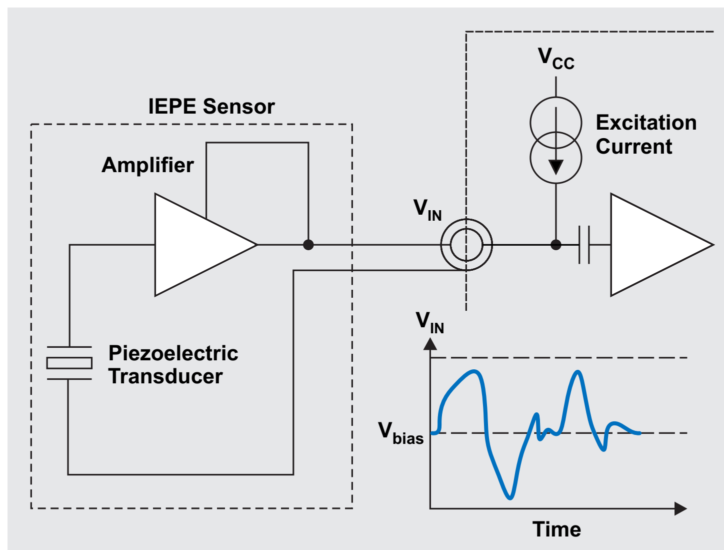
Introduction

Machine failure is very costly in a production environment. The industry is actively transitioning from scheduled preventive maintenance toward predictive maintenance, which can proactively detect potential machine failure through condition monitoring of temperature, vibration and other parameters.

Several theoretical and empirical models can link these condition parameters to a machine's health status. Condition monitoring greatly optimizes maintenance cost and decreases machine downtime.

Vibration sensing is a cornerstone of condition monitoring, with integrated-electronics piezoelectric (IEPE) sensors dominating mainstream industrial applications. The IEPE-sensor interface, however, demands higher performance not met by the analog input of the typical programmable logic controller (PLC). High resolution, high sensitivity and high speed are among the features defining the IEPE-sensor interface as a classic data-acquisition system rather than as a PLC analog input.

Figure 1. IEPE sensor conceptual circuit



Understanding IEPE vibration sensors

A piezoelectric transducer converts mechanical acceleration into a small capacitance change, which is susceptible to noise because of its high output impedance. A charge-amplifier circuit converts the low-level capacitive change into a high-level voltage signal. An IEPE sensor is a piezoelectric vibration transducer with a charge amplifier and impedance converter. Integrating the amplifier and sensor greatly reduces the sensor noise. One major advantage of the IEPE sensor is that it is interchangeable and has similar interface requirements among sensor manufacturers. Figure 1 shows a simple circuit of the IEPE sensor and how it is powered.

An external constant current, preferably integrated with the interface, powers the IEPE sensor. The output signal is an AC signal on top of a constant DC voltage called the bias voltage. This configuration allows a two-wire cable to carry both the sensor power and signal. Given the existence of the DC bias, the signal is typically AC-coupled to the interface circuit.

IEPE sensors have a wide range of performance parameters, including:

- Sensitivity – The output voltage change that corresponds to a specific mechanical-acceleration input measured in millivolts per acceleration of gravity (g). Sensitivity variations due to temperature, input frequency and input level are known as the sensitivity tolerance and is represented as a percentage of the full range. IEPE sensors with sensitivity between 0.05 mV/g to 10 V/g are available.
- Output-voltage and measurement range – The measurement range is the difference between the maximum and minimum acceleration input that the sensor can convert to a voltage output without saturation or clipping. The relationship between measurement range and output voltage range is:
  - Output voltage range (V) = measurement range (g) × sensitivity (V/g).
  - The typical output range of an IEPE sensor is ±5 V to ±10 V and represents a measurement range from microns of acceleration of gravity to hundreds of acceleration of gravity.
- Output bias voltage – The DC voltage at the sensor output when powered by the rated current source. It is independent to some degree from the biasing current and typically in the 8-V to 12-V range.

- Excitation voltage – The compliance range of the current source or maximum DC voltage allowed on the output without affecting the current source. This value makes sure that the sensor-interface front-end properly receives the sensor output (including AC + DC) without clipping.
  - $Excitation\_voltage_{min} = Bias\_voltage_{max} + Sensitivity \times Output\_range_{max}/2$
- Frequency response – The sensor translates acceleration into voltage within a certain frequency range where sensitivity is constant. Beyond the maximum frequency, the sensor has a mechanical resonance frequency that should be avoided. The usual frequency range is sub-hertz to 10, 20 or 30 kHz. A sensor interface circuit should have the same bandwidth as the targeted sensor, and the analog-to-digital converter (ADC) sampling frequency should be more than twice this bandwidth.
  - The cable that connects the sensor to the front end will have an impact on the 3-dB sensor bandwidth and useful frequency range. Increasing the excitation current can extend the frequency range for longer cables.

System overview

The IEPE-sensor characteristics are a good starting place for determining the specifications for an analog front end. If the input signal is about ±10 V and the ADC input signal is ±2.5 V, the front-end signal-chain's overall gain will be about one-fourth; however, different applications might require variable gain. The existence of bias voltage is better handled through AC coupling and a high-pass filter with a low cutoff frequency. The resolution of the front end (usually 14-bit up to 24-bit) is directly related to the uncertainty in the measured acceleration value. The dynamic range of the chain is set not by the resolution, but rather by the noise level on the lower side and the converter full scale on the upper side—reaching 100 dB (effective number of bits [ENOB] = 17) for high-end front-end products.

The chain bandwidth should match the sensor's flat sensitivity range, which lies between 10 kHz and 30 kHz. The bandwidth determines the anti-aliasing filter as well as the converter sampling speed or output data rate. A constant and stable current source over the whole sensor's output-signal range (0 V to 22 V) dictates the minimum supply voltage for the current source. While a 2- to 4-mA current source is sufficient to operate the majority of IEPE sensors, a variable current source is necessary to broaden the applicability of the front end to a variety of cables and cable lengths.

Combining the previously described elements results in the diagram in Figure 2 and the specifications in Table 1. For the anti-aliasing filter, because the ADC is sampling the noise at clock frequency and folding back to the 20-kHz attenuated signal band, high-level attenuation is required from that filter at the clock frequency.

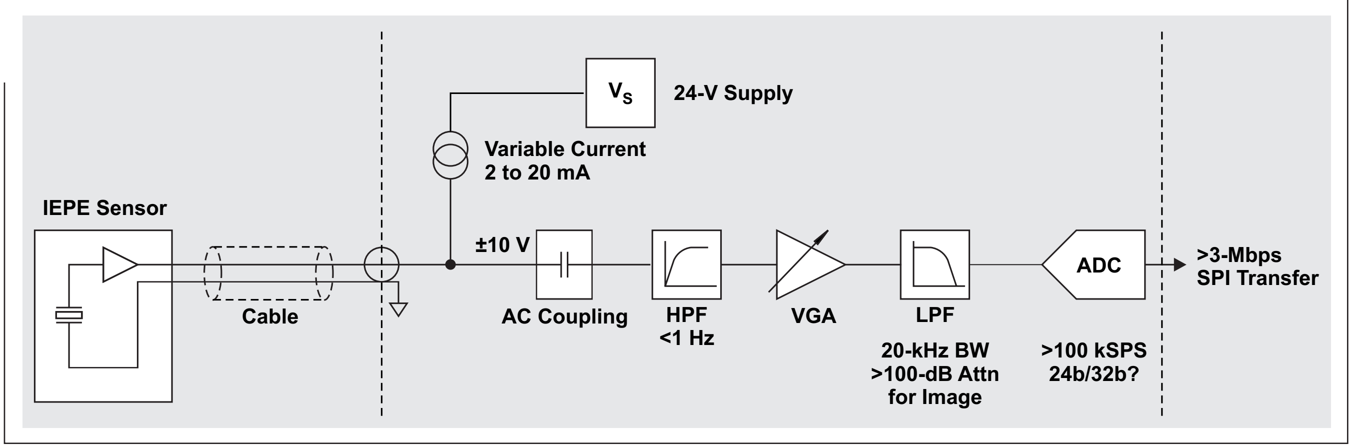
Table 1. Front-end target specification

	Target Specs
Resolution	24
Sampling rate	>100 kSPS
Input range	±10 V
Bandwidth	20 kHz
High-pass filter	0.6 Hz
Signal-to-noise ratio (SNR)/dynamic range (DR)	100-dB DR
Coupling	AC
Input impedance	250 kΩ
Bias current	2 to 20 mA
Temperature range	–40°C to 80°C

Converter requirements

The 30-kHz bandwidth requires an ADC with a resolution higher than 20 bits and a sampling speed greater than 100 kSPS to achieve the target 100-dB SNR. A sigma-delta ADC with an integrated filter is preferred, however, a successive approximation register (SAR) converter is also an option. An integrated, wideband digital filter with a flat

Figure 2. Simplified IEPE sensor interface



response over bandwidth will be a plus, as it takes a lot of burden from the controller processor when using a sinc filter.[1]

The data-capturing controller should support the high-speed data transfer of the serial-peripheral interface (SPI) and have enough memory for data storage. If the execution of a fast Fourier transform is required in real time on the same processor, factor that in when determining the processing power. A SPI master with a data rate of at least 3 Mbps is required to collect data from the ADC for 24 bits at 100 kHz. The ADC input impedance will set the upper limit of the driver-stage output impedance, and the reference voltage will set the upper limit of the driver-stage output swing.

After selecting an ADC, it is important to select the reference scheme to be internal or external, the reference level, and the clock frequency to get the maximum SNR of the ADC at a given input bandwidth and dynamic range of the input.

ADC driver and anti-aliasing filter

The ADC driver:

- Converts a single-ended signal to a differential signal.
- Scales the input and adjusts the output common-mode level so that the ADC input signal spans the ADC full scale in case of maximum input.
- Implements the necessary anti-aliasing filter.
- Acts as an impedance buffer and ensures a low-impedance drive for the ADC.
- Combines these functions into one block for a more compact implementation.

The single-ended-to-differential conversion dictates a minimum gain of 2 V/V; the same single supply limits both single-ended and differential signals. A fixed gain provides better noise performance and avoids the complexity of variable-gain filters. The input signal to the filter is single-ended to reduce complexity and footprint.

For an 8-MHz clock frequency and 20-kHz signal band, the transition band is log(8 × 106/24 × 103) = 2.6 decades. A one-pole filter would provide 20-dB/decade attenuation and a second-order filter would result in 104 dB of attenuation over the transition band. However, adding a third-order pole with a simple resistor-capacitor filter stage achieves the target 110-dB attenuation and adds some margin to accommodate for any degradation caused by amplifier-limited bandwidth, temperature drift or passive-component variances.

To keep the passband as flat as possible, a Butterworth approximation filter is the optimal choice. Among different realizations, a multiple-feedback filter (MFB) provides a single operational-amplifier (op amp) implementation with improved noise performance. The trade-offs are some restrictions on the design (Q and f_C are coupled) and more sensitivity to op-amp performance and passives tolerances. Using precision components overcomes the passives sensitivity, while a high gain-bandwidth (GBD) amplifier diminishes the op-amp effect.[2]

For an approximately 20-kHz pole, an amplifier with a GBW > 20 MHz would ensure proper attenuation at an 8-MHz image frequency. Figure 3 shows the results of TI's FilterPro™ software synthesizing the required filter.

Figure 3. Designing the anti-alias filter using FilterPro™

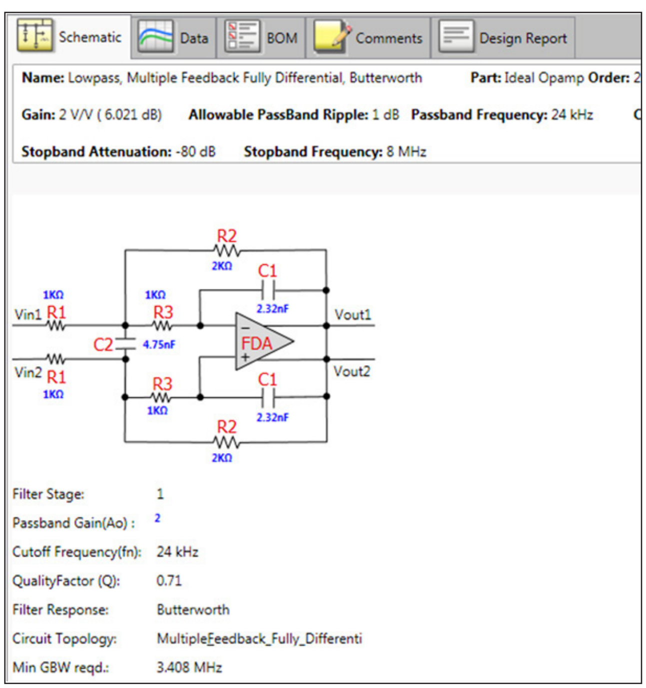


Figure 4 shows the actual implementation using the THS4551 fully differential amplifier, E192 0.1% resistors (E96 1% is an option) and C0G/NP0 5% capacitors. Adding a small capacitor to the input improves noise performance and a couple of small resistors at the output improves amplifier stability. The third pole is a simple RC filter with R = 10 Ω and C = 22 nF, which can be added to the output of the circuit in Figure 4. As a single-ended-to-differential converter, one input of the amplifier connects to the common-mode voltage (Vcom), which at the mid supply maximizes the input ADC range with the best linearity.

The TINA-TI™ software Monte Carlo circuit simulation shown in Figure 5 shows an accurate 20.55 ± 0.15-kHz bandwidth, a minimum –110-dB image rejection at 8 MHz, an output impedance of 25 ± 5 Ω and an input impedance of 1.3 kΩ with a minimum –100 dB of supply rejection.

Figure 4. Actual implementation of filter/ADC driver stage

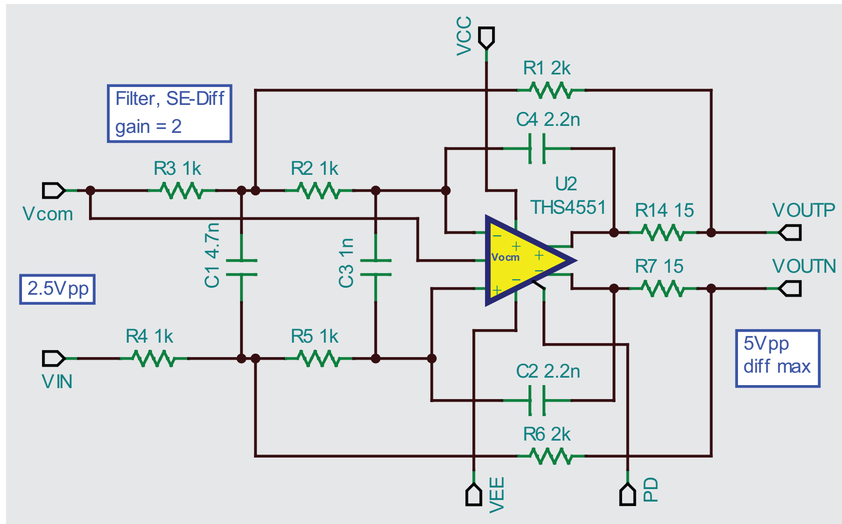
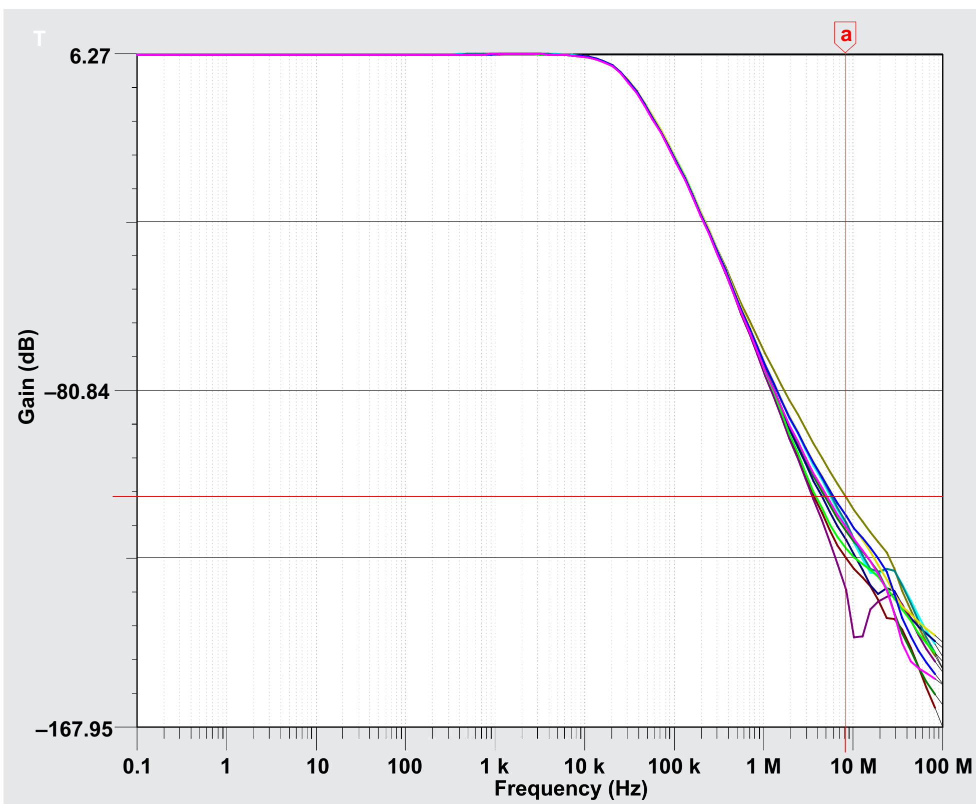
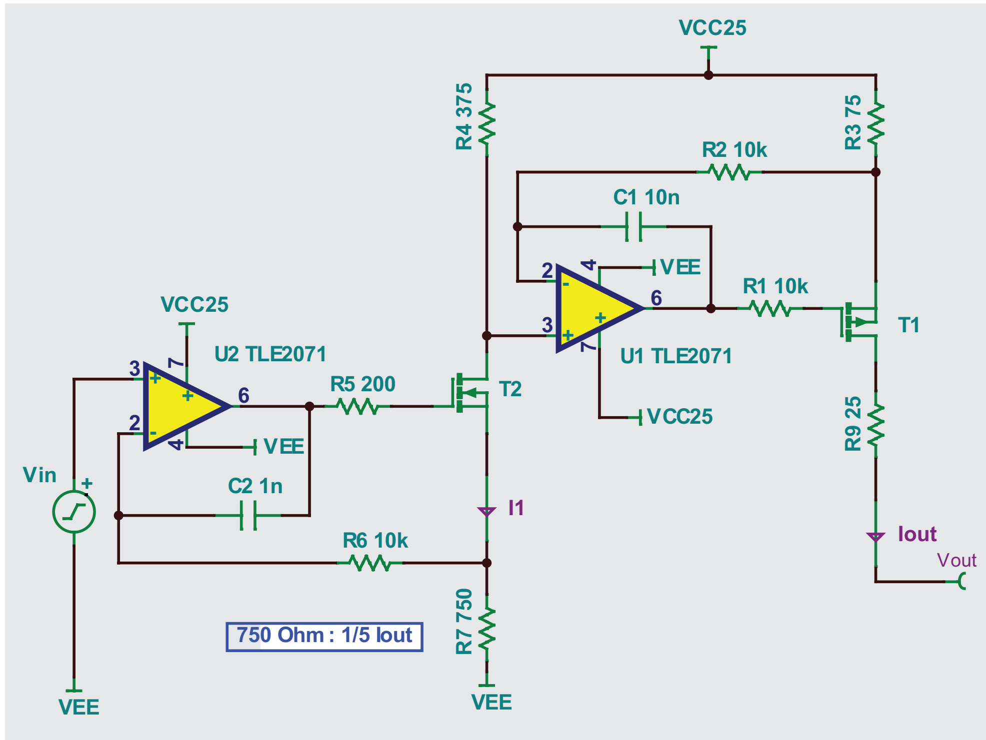


Figure 5. Filter AC simulation



Current source

Figure 6. High-side current source



The current source's main challenge is being a high-side source with a high-compliance-range voltage. As previously mentioned, digital programmability is very useful to serve different types of sensors and cables. Although absolute accuracy is not important, stability over the temperature range, supply voltage, and output voltage is important because the current change in these parameters will be interpreted as vibration input.

Constant-current diodes and discrete transistors are the simplest option for constant high-side current generation. A current reference is another option, but costly and not really required. A dedicated voltage-to-current converter can be used, but it might be inferior regarding noise. A simple op-amp voltage-to-current converter is an easy and flexible solution for configurable current, with a reasonable power consumption and footprint.

The circuit in Figure 6 allows the choice of input range and intermediate current in R7. For low headroom and a high compliance range, the circuit requires a high-voltage rail-to-rail op amp. The U2 op amp converts Vin to $I1 = Vin/R7$. R4 converts I1 back to a voltage $Vm = Vin \times R4/R7$. The U1 op amp converts this voltage back to a current, $Iout = Vin \times R4/(R7 \times R3)$.

The selection of proper values for the resistors achieves the proper scaling (3 V to 20 mA) while maintaining the voltage headroom at the output minimum and keeping I1 current low. The output noise is proportional to Iout/I1, so there is a trade-off between power consumption and noise performance. Moreover, there is a trade-off between the power-supply rejection ratio (PSRR) and output voltage headroom on R3. This circuit achieves a PSRR better than 70 dB in the band of interest.

To implement the configurable current, a simple low-resolution SPI-controlled digital-to-analog converter (DAC) can serve as the input to the first U2 op amp, enabling low-cost digital control for the high-voltage current source.

Conclusion

PLC input modules for condition monitoring are currently on the rise. This article took step-by-step approach to build the knowledge needed in defining an analog interface for an IEPE vibration sensor while considering the design trade-offs.

References

1. Brian Pisani, "Digital Filter Types in Delta-Sigma ADCs," Texas Instruments Application Report (SBAA230), May 2017.
2. Michael Steffes, "Design Methodology for MFB Filters in ADC Interface Applications," Texas Instruments Application Report (SBOA114), February, 2006.

Related Web sites

Reference design:
IEPE Vibration Sensor Interface for PLC Analog Input

Design tools:
FilterPro™ WEBENCH® Active Filter Designer
TINA-TI™ Spice-Based Analog Simulation Program

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