Using the ispPAC81 to Suppress Out-of-Band Sensor Resonance

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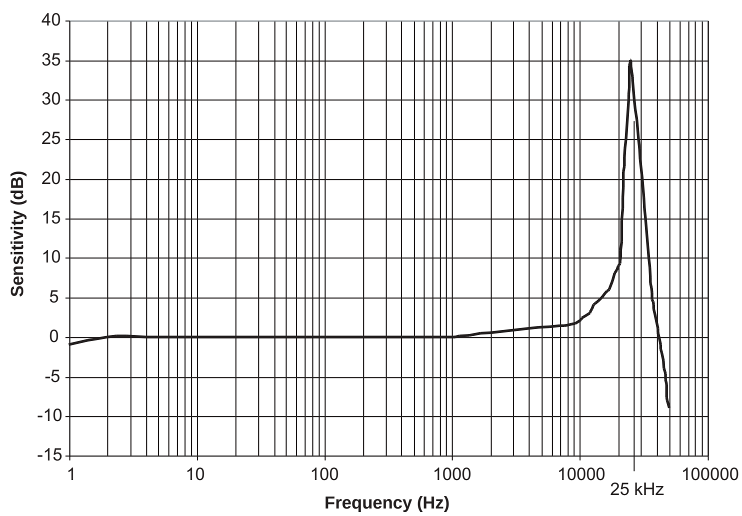
Overview

This application note describes both how and why the ispPAC®81 should be used to filter out transducer resonance from vibration sensors. This note discusses the key features of the ispPAC81 that make it an excellent choice for this type of application and also examines specific issues that pertain to the field of vibration analysis. A brief background about piezoelectric sensors and resonance is also provided as well as several circuits that interface accelerometers, velocity sensors, and piezoelectric transducers directly to the ispPAC81.

Introduction

The ispPAC81 is a single IC that provides 5th order lowpass filtering with corner frequencies programmable from 10.8kHz to 77kHz with no external components. This device operates on a single +5V supply and can be programmed and reprogrammed (typical 1M writes) while in-circuit. It provides an instrumentation amplifier front end with selectable gains of: 0dB, +6dB, +10dB, and +20dB. The input amplifier, filter block, and output amplifier are implemented using a differential topology that provides a system-level noise immunity that is unparalleled in a discrete or OP-AMP solution. The filter is a time-continuous type that does not require clocks and therefore does not introduce harmonics into the signal path like switched-capacitor filters are prone to do. The ispPAC81 can be programmed to hold configuration information for two separate filters ('A' and 'B'), thus providing two filters in one chip. The ispPAC81 can be programmed and simulated using PAC-Designer® (a Windows-based design utility), which simplifies complex analog filter design to a point-and-click process. Pre-designed filter types of Butterworth, Chebyshev, and Elliptical are available from the database of over 2000 filter configurations contained within PAC-Designer. The ispPAC81 extends the range of the ispPAC80 from 50kHz down to 10kHz, which answers the call of many circuits for a high-order lowpass filter. One such application is limiting the bandwidth of a vibration analysis system by placing the ispPAC80 between the vibration sensor and the data acquisition system. The benefits of using a lowpass filter in this kind of application are multi fold. Primarily, the reduction of resonant signals enables the vibration signals of interest to fill the dynamic range of the data acquisition system. Secondly, the reduction in the input bandwidth results in less front-end noise and a lower noise floor, which also improves the signal to noise ratio (SNR). Lastly, the purity of the vibration signal is increased due to the reduction of the resonant component.

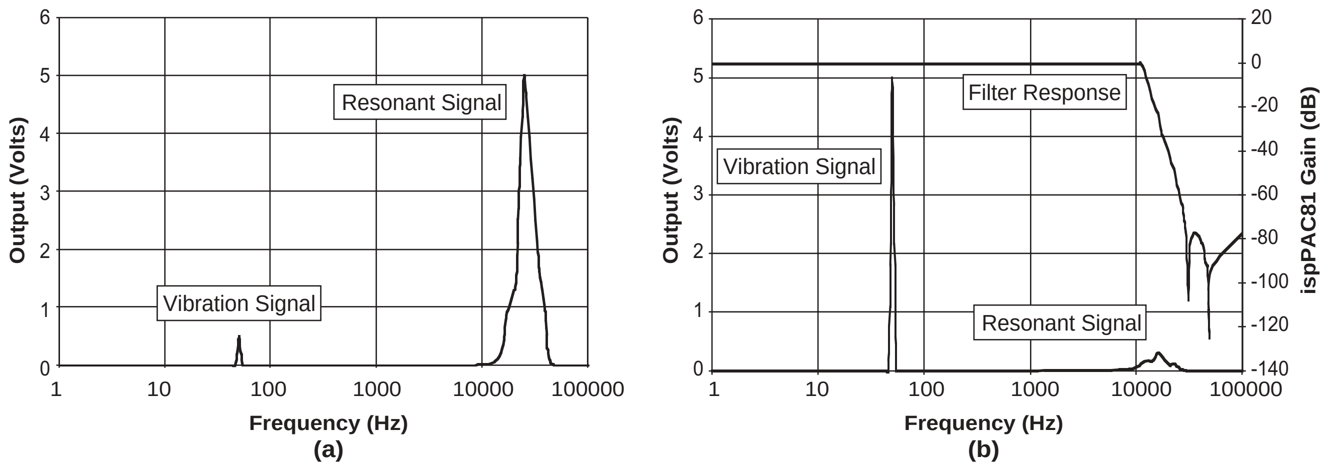
Figure 1. Typical Response of a Vibration Sensor Showing Resonant Peak



All piezoelectric vibration sensors have a natural resonance (much like a tuning fork) which can be excited by harmonics of the fundamental vibration of interest or other sources of vibration or noise. The sensor is far more sensitive at the resonant frequency than anywhere else, as shown in Figure 1. Before we discuss an example of how the ispPAC81 electronically filters the resonant signal, it is worth mentioning that some sensor manufactures market mechanical filters. These mechanical filters isolate the sensor from the vibration source with a layer of rubber, whose properties are a function of both temperature and age. The ispPAC81 exhibits consistent and predictable behavior both over temperature and age, as well as from device to device.

Consider for example, monitoring the vibration of a flywheel near an engine. If the flywheel is spinning at 3,000 RPM, the signal of interest is about 50Hz. Let us also assume the vibration level is around 0.5 inches per second (IPS). A typical sensor would produce a signal level of 10mV. When engine noise is coupled to the sensor, it can excite a resonant mode in the sensor and produce a signal level of 0.1V, swamping out the signal of interest, as shown in Figure 2(a). If a 12-bit analog to digital converter is being used with a full-scale input of 5V, the resulting resolution is 0.00122 IPS per bit. Thus, our vibration signal amounts to 409 bits out of 4096.

Figure 2 Signal Levels Without and With ispPAC81



In Figure 2(b) the output of a vibration sensor has both been processed by an ispPAC81 and gained by a factor of 10. The ispPAC81 was configured as an Elliptical lowpass filter with a corner frequency of 11.8kHz. In this example, there is an apparent shift in the resonant peak. This is because the resonant signal has a broad base and occurs between the pass-band and stop-band of the filter. The resonant peak is attenuated by more than 55dB; however, the effective reduction in resonant noise is 44dB and the 50Hz signal of interest is passed with no attenuation. The resulting resolution is increased by a factor of ten (0.000122 IPS per bit), and the vibration signal uses all 4096 bits of the ADC. This increase in resolution makes accurate measurements possible when performing maintenance activities or dynamic balancing, as will be discussed later.

Background

I. Piezoelectricity.

Jaques and Pierre Curie first discovered the piezoelectric effect in 1880 as the change in electric field within a material, which results from of a change in applied force. Naturally occurring materials that exhibit piezoelectricity include quartz and Rochelle salt. These materials are also insulators, so electrical plates are attached to sense the change in electric field (Figure 3). The electrical plates also form the basis of a capacitor where the piezoelectric material is the dielectric. The changing field between the capacitor plates results in a transfer of charge Q. Figure 3 illustrates the charge flow that occurs when tension and compression are applied to a piezoelectric transducer. The active materials used in most vibration sensors are synthetic ferroelectric ceramics that can be fabricated in a variety of shapes, sizes, and strengths. One of the more popular ceramic is PZT Lead-Zirconate-Titanate. The typical sensitivity of PZTs used in vibration sensors is around 300 pico Coulombs per newton. The high impedance and low noise input of the ispPAC81 makes it ideally suited to amplify such small signals. In most sensors, the piezoelectric material is sandwiched between the base and a seismic-mass, as shown in Figure 4.

Figure 3 Schematic Diagram of Piezoelectric Material

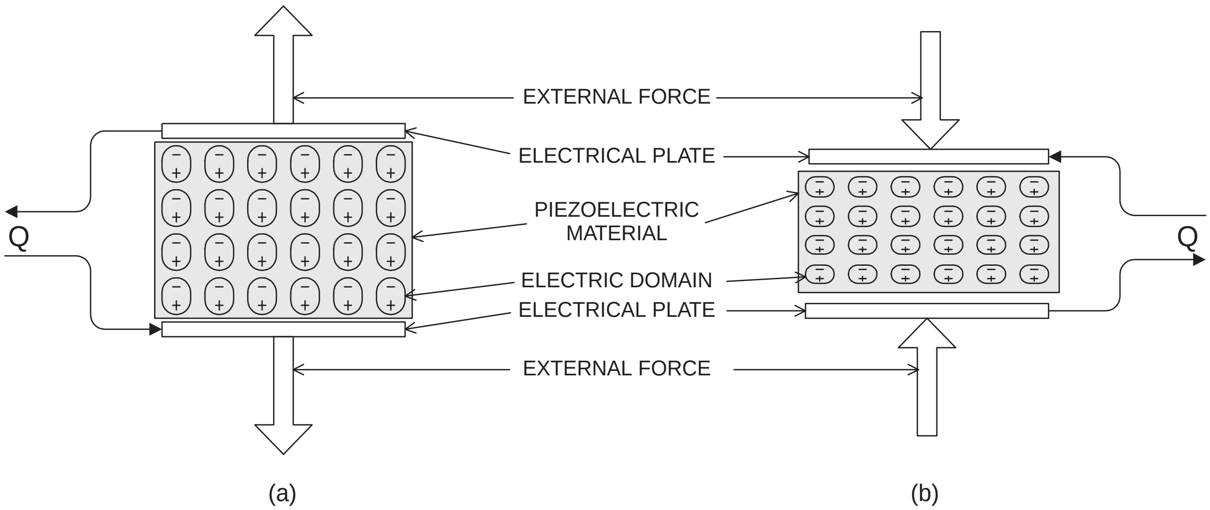
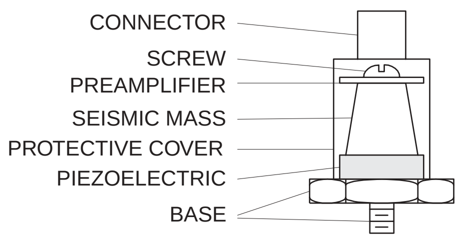


Figure 4 Inside View of Vibration Sensor



II. Resonance

Mechanical resonance can be summarized by Equation 1, where f is the frequency in Hertz, k is the restoring force, m is the mass.

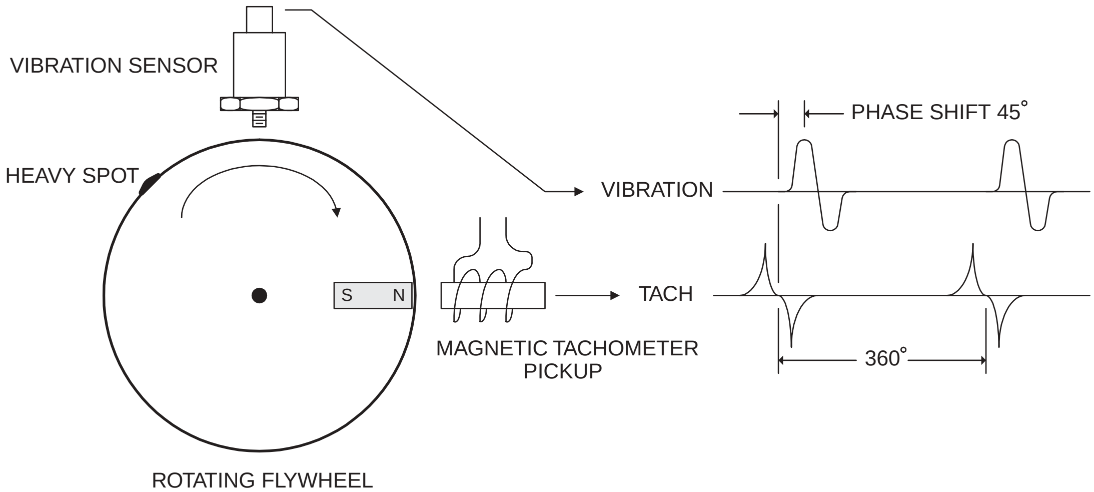
$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

In crystals that are used in electronic oscillator circuits, the mass of the metal plates (similar to Figure 3) is very low and the stiffness of the quartz crystal is very high. Thus the mechanical resonance (which is stimulated by a circuit) is in the MHz range. In vibration sensors the seismic mass is more massive than a metal plate, which results in resonant frequencies down in the 20kHz to 75kHz range. Sensors are stimulated into resonance mechanically by either by high order harmonics, or by the effect of non-linear distortion on the low frequency vibrations. When the vibration (imbalance or worn spots of the rotating machinery) occurs at an even sub-harmonic of the resonant frequency, the resulting amplitude at resonance far exceeds that of the fundamental. This effect is known as flutter and was demonstrated by the classic example of the Tacoma Narrows Bridge disaster. In 1940, a 42-mph wind excited a mechanical mode, and shook the bridge to destruction. Using the ispPAC81 will not prevent mechanical failure, however it can help in accurately determining modes of instability in similar structures.

III. Balancing

Dynamic balancing is achieved by measuring the amplitude and phase of the fundamental vibration signal, as shown in Figure 5. Fundamental vibrations are a direct result from the imbalance of the rotating machinery, hence they occur at same frequency as the rotation. The phase of the signal is measured relative to a tachometer signal which also occurs once per revolution (in Figure 5 it is 45 degrees). The magnitude of the signal is an indicator of how much adjustment needs to be made, and the phase of the signal indicates where to make it. In the example of Figure 5, some of the excess mass would be removed at the heavy spot to bring the wheel into balance. When using a filter such as the ispPAC81 in this type of application, the phase shift needs to be constant over the range of useful frequencies. Then a software algorithm can be used to remove the constant phase shift and compute the actual phase of the signal. The ispPAC81 can be configured to implement different filter types, which exhibit different phase characteristics. For this example, the optimal choice would be a 10.8kHz Butterworth, which provides both maxim flatness and minimal phase shift within the frequency range of interest. Additionally, resonant signals above the corner frequency are attenuated at the rate of 100dB per decade; thus improving both the accuracy and resolution of the vibration measurement.

Figure 5 Balancing a Flywheel and Respective Signals



IV. Maintenance Activities.

Quite often FFTs are used in trending vibration signatures as part of routine maintenance: because, additional frequencies are being monitored along with the once-per-rev. For example, if a shaft is supported by a roller bearing with 10 rollers and one roller starts to develop a gouge in its surface, there will be a 10-per-rev component in the signature. Furthermore, the source of the signals may be a bit removed from the bulkhead where the sensor is mounted, thus wide dynamic range and low noise instrumentation are basic requirements of the front end analog electronics that process the vibration signals. The ispPAC81 meets these requirements and more. For maintenance activities, the optimal filter type would be Elliptical with a cut off frequency of 11.8kHz. This filter type has a steeper transition from the pass band to the stop band and attenuates everything above 30kHz by 80dB or more. The phase shift is less constant than in the case of the Butterworth; however, for this type of measurement the phase information is less important. If an instrument is used for both balancing and vibration trending, the ispPAC81 can be used to hold both the Butterworth and Elliptical filter configurations and switch between the two. Again the reduction of the resonant component significantly improves the accuracy and resolution of the vibration signature analysis.

V. Bandwidth and Noise Considerations.

Two added benefits of using a high-order lowpass filter to block sensor resonance, are that it also performs the function of an anti-aliasing filter (as long as the ADC is sampling at twice the filters corner frequency) and lowers the input noise. For example, if the ispPAC81 implements a filter with a 10kHz corner frequency to block sensor resonance at 25kHz, then the total RMS input noise can be estimated using Equation 2.

$$\text{RMSnoise} = \sqrt{\text{BANDWIDTH}} \times 70\text{nV} / \sqrt{\text{Hz}} \tag{2}$$

This results in 7μV. In a 5V-based ADC this corresponds to 117dB SNR, which corresponds to about 19 ADC bits. The sampling rate can range from 20kHz up to what ever is required for the frequency resolution of the FFT and analysis. Conversely, if a system were sampling at the rate of 1,000,000 times a second, the anti-aliasing filter would be set to 500kHz. If a filter designed for that frequency had the same noise density as the ispPAC81, the resulting input noise would be 49μV. Using the same 5V ADC, this is equivalent to 100dB of SNR (or 16 bits), a degradation of 17dB (3 bits). In any case, the noise from the ispPAC81 won't be the weak link in the signal chain.

Vibration Sensor Bias and Interface to ispPAC81

In this section we discuss the interface of the vibration sensor output to the input of the ispPAC81 and discuss some biasing issues. The two basic sensor types are the internally amplified, and the non-amplified. The non-amplified (vibration transducer) can be wired as single-ended output or differential output. The amplified (vibration sensor) must be powered or biased by a constant current or constant voltage. In the amplified case, the output signal has a DC bias that can exceed the input rating of the ispPAC81. The circuits that follow illustrate these issues and the input biasing of the ispPAC81.

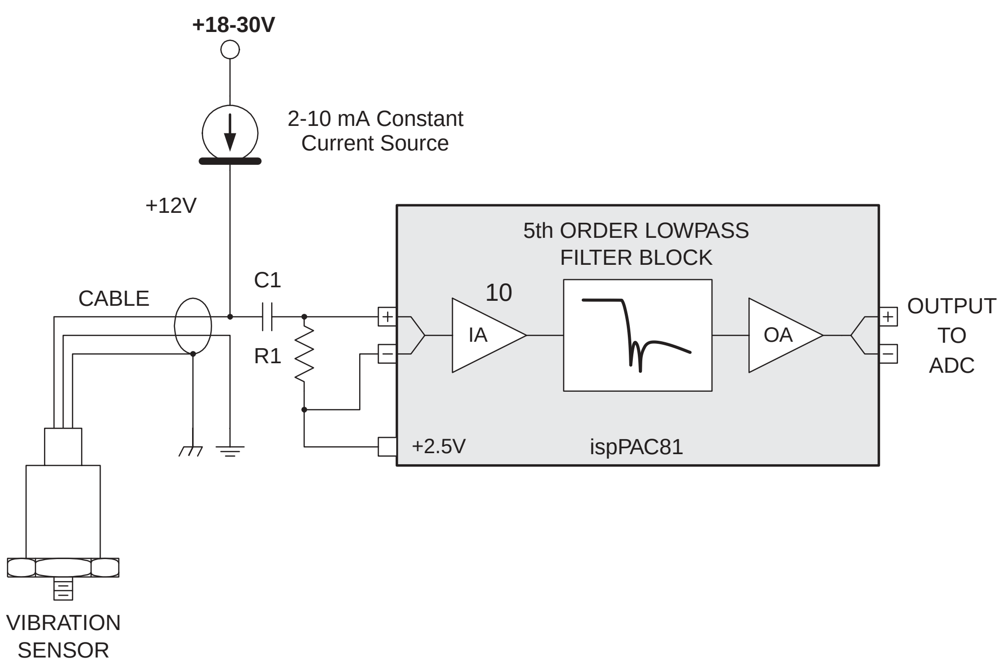
I. Accelerometer powered by a constant current.

Figure 6 shows a vibration sensor powered by a constant current diode connected to a supply with enough compliance. The output of the sensor is an AC voltage with a DC bias around 12V. The ispPAC81 input voltage range is 1V to 3V. Therefore, C1 and R1 form a first order high pass filter, both to block the DC bias and to establish the low end of the bandwidth. The corner frequency f_c is given by Equation 3.

$$f_c = \frac{1}{2\pi R1C1} \tag{3}$$

Since 1.0 Hz corresponds to 60 RPM, the high-pass corner may need to be set to a fraction of a Hertz for many applications. Typical values for C1 and R1 might be 15μF and 100 kΩ to set the corner around 0.1Hz. The $VREF_{OUT}$ (shown as the +2.5V pin in Figure 6) is only capable of sourcing 50μA and sinking 350μA; thus the value of R1 should be chosen with that in mind.

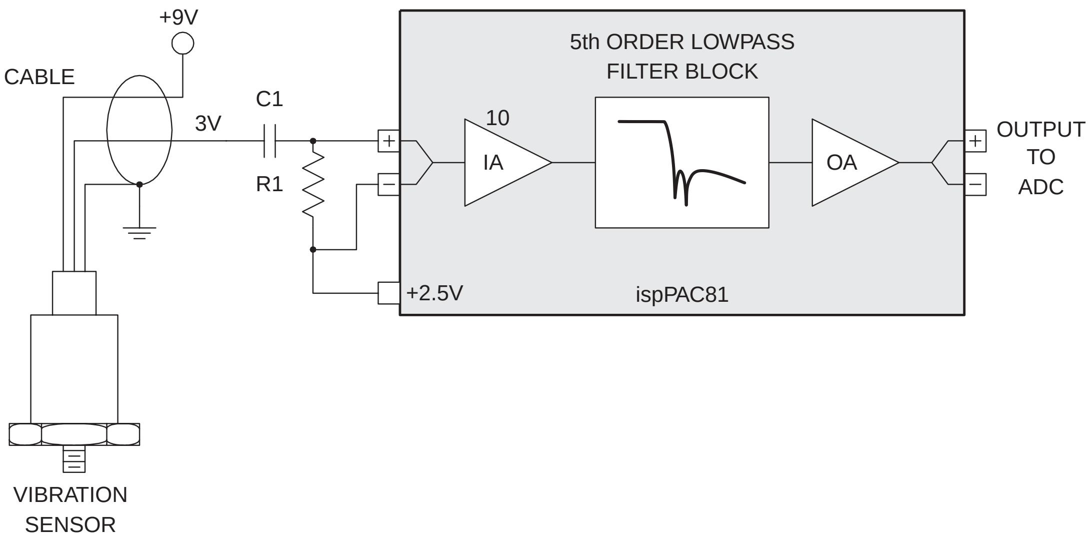
Figure 6 Constant Current Powered Sensor Interface to ispPAC81



II. Velocity Sensor powered by a constant voltage.

Figure 7 illustrates a vibration sensor powered by a constant voltage. The output of this sensor is an AC voltage with a DC bias typically ranging from 3V to 5V. As in the previous example, the input voltage range of the ispPAC81 is 1V to 3V. Again, C1 and R1 both block the DC bias and form a first order high pass filter. Recommended values for C1 and R1 are the same as the previous example (15μF and 100 kΩ) to set the highpass corner around 0.1Hz.

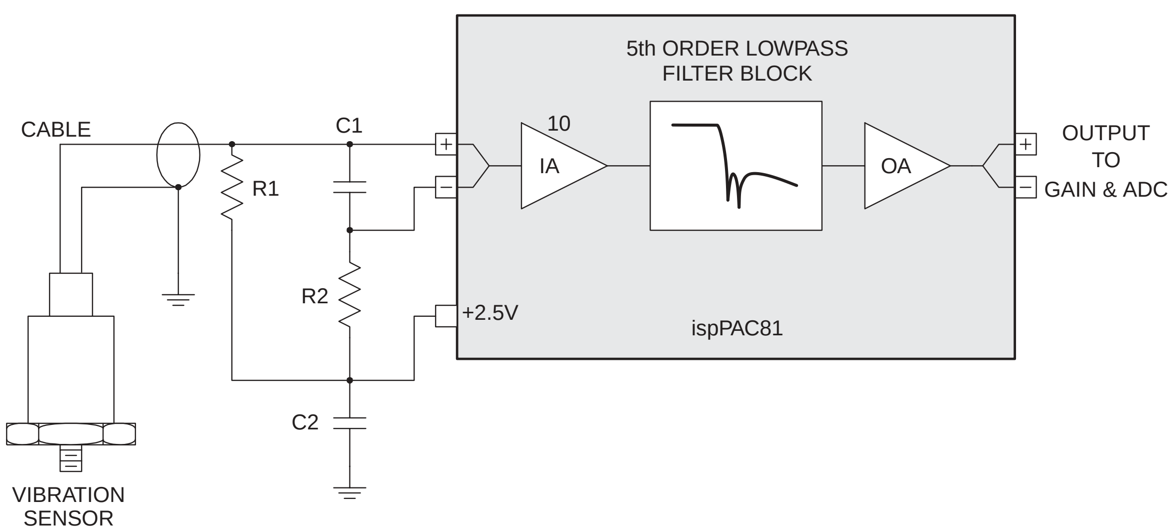
Figure 7 Voltage Powered Vibration Sensor Interface to ispPAC81



III. Single-ended Charge Output

Figure 8 shows an acceleration transducer whose output signal is in the range of pico Coulombs-per-gravity. C1 converts the single ended output charge to a voltage that is amplified by the IA. R1 and R2 bias the ispPAC81 inputs using its own reference output. C2 filters the reference output and provides an AC low impedance path (typical values of 0.01µF are recommended). The network of R1, R2, and C1 form a simple highpass filter with a corner frequency that can be predicted by the series combination of R1 and R2. If C1 is 1,000pF for example, the resulting charge gain (including the IA gain of 10) is 5.0 milli-Volts-per-pico-Coulomb. If both R1 and R2 are set to 10MΩ, the resulting corner frequency is around 8Hz. If the vibration level is low and/or the charge sensitivity of the transducer is low, additional gain can be obtained using other ispPAC devices that have differential inputs and programmable gain.

Figure 8 Charge Output Sensor Interface to ispPAC81

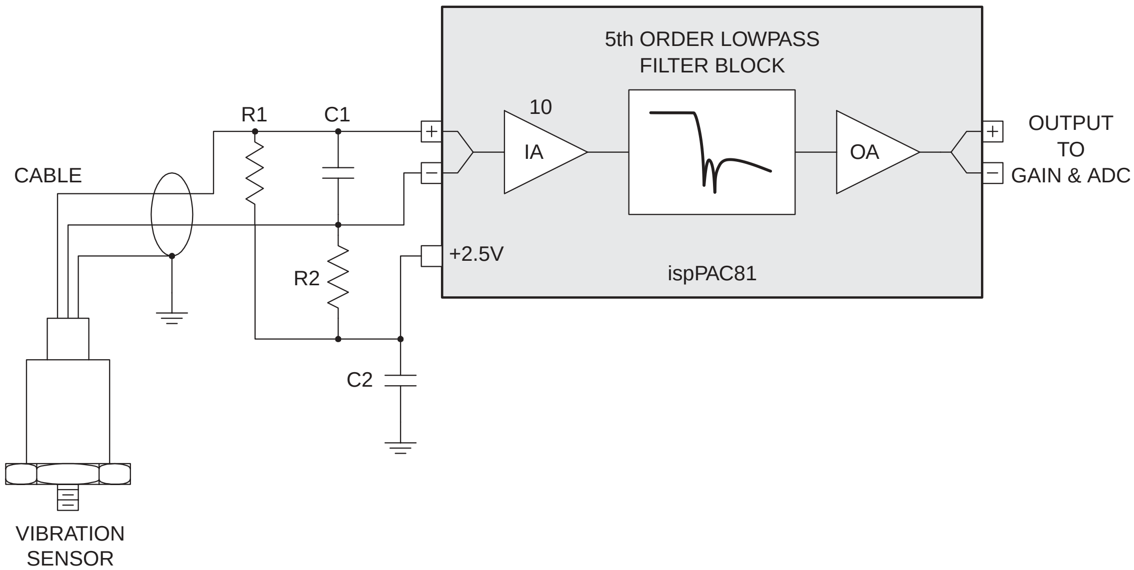


IV. Differential Charge Output

When both sides of the piezoelectric are isolated from the case of the vibration transducer and brought out through the connector, the output is a true differential signal, which is an ideal source for the ispPAC81 inputs. In Figure 9, the capacitor C1 converts the differential output charge to a voltage that is amplified differentially by the IA. R1 and

R2 bias the ispPAC81 inputs to 2.5V from its own reference output, which is typically filtered with a 0.01µF capacitor (C2). As in the previous example, C1, R1, and R2 form a highpass filter. Using the same example values of 1,000 pF for C1, and 10MΩ for both R1 and R2 results in a charge gain of 10.0 milli-Volts-per-pico-Coulomb and a corner frequency of 8Hz. While the increase in charge gain (over the single ended circuit in Figure 8) is a by-product of interfacing a differential source to a differential amplifier, the real benefit is the increase in noise immunity offered by differential signal handling. Bringing the low-level signals from the transducer to the amplifier by two side-by-side wires tends to null out common mode electric or magnetically coupled noise, because both (+) and (-) inputs of the differential IA see the noise together. For additional information regarding differential signals, please see Lattice application note number AN6019, *Differential Signaling*.

Figure 9 Differential Charge Sensor Interface to ispPAC81



Summary

In this application note, we have seen the importance of reducing the amplitude of signals that result from the transducer resonance, because it improves the accuracy and dynamic range of the signals we are measuring and the SNR of the system. The ispPAC81 has shown us the benefit of storing two different filter configurations and switching between the two, based on the type of measurement being made. We have seen that a minimal number of passive components are used to interface a variety of vibration sensors and transducers, while no external parts were required to set the filter characteristics; thus providing a compact integrated filter/amplifier solution. The ispPAC81 provides consistent repeatable filter characteristics that are temperature stable and time continuous. Using PAC-Designer, complex 5th order lowpass filters can be designed and simulated with the click of a button.

References

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