A High-Precision Low-Cost Analog Acceleration and Vibration Amplifier using PVDF Piezoelectric Sensors

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Abstract

This paper describes a high-resolution analog acceleration and vibration amplifier for use with piezoelectric polyvinylidene fluoride (PVDF) sensors. The purpose of this system is to monitor automated parts placement on integrated circuit boards. One of the problems facing production and inspection equipment is the occurrence of resonant and ambient vibrations. Even small errors can cause systems with micrometer and nanometer precision to exceed design tolerances. This work describes a method to monitor mechanical vibrations through a portable and inexpensive signal-processing unit. The system provides user-selectable gain and filtering modules that are compact and reliable. PVDF is currently used in sensing applications, and its material properties have proven very useful for sensing mechanical stress, strain, pressure, and temperature.

Index terms—PVDF, piezoelectric film, vibration sensing, Sallen-Key

1 Introduction

As the integration level of electronic systems increases and becomes more sophisticated, producing these devices grows more complicated and expensive. Not only does fabrication become increasingly difficult, but inspection and testing are also more demanding. One of the problems facing automated production and inspection equipment is resonant and ambient vibration. This work describes a method to monitor mechanical vibrations through a portable and inexpensive signal-processing unit. The system provides user-selectable gain and filtering modules that are compact and reliable. PVDF is currently used in sensing applications, and its material properties have proven very useful for sensing mechanical stress, strain, pressure, and temperature.

This property makes the material an effective candidate for use in the construction of vibration and acceleration sensors [2]-[7]. There are, however, some disadvantages when working with PVDF. Not only does it exhibit a high piezoelectric constant, but also a considerable pyroelectric constant, indicating that the material produces high voltage variations when exposed to changes in temperature. There can be as much as an 8-volt change in output voltage per degree Celsius [8]. This can be managed with a combination of shielding and a DC offset control. PVDF material is also highly capacitive and is sensitive to IR and RF interference, but careful design can reduce these effects. All of these potential problems were considered and addressed in the finished system. Initially, several currently available designs were evaluated to investigate the properties of PVDF sensors and the signal processing characteristics of the associated amplifiers [9]. Improved amplification and conditioning circuitry was designed, constructed, and tested for use with several types of these sensors. Frequency response, dynamic range, and measurement axes are important, but cost is another important factor. The analog system described here is robust, low-cost, and portable. It can employ batteries, a single +5volt supply, or a plug-in wall adapter. Excessive vibrations are indicated through a simple LED arrangement, or the system can be connected to a data acquisition recorder for time and/or frequency analysis. The specifications for the overall system are illustrated in Table 1.
2 System Design

This design is composed of seven blocks, which are described in the following subsections. The high-pass and low-pass filters are of similar configuration. Therefore, only the high-pass filters will be described in detail. Component values are included for all of the filtering elements. A block diagram of the conditioner is shown in Fig. 2. One specification required of this design is that it operates from a single 5-volt DC power supply. Therefore, a Newport NMA0512S one-watt to DC-to-DC converter was employed to power all components. This model has an internal oscillation frequency of 100 kHz, which is well beyond the frequency ranges being monitored. The low-power design presented here lends itself to battery operation, which is advantageous over plug-in wall adapters because of AC line interference.

3 b) Input impedance control

High input impedance is necessary to successfully measure PVDF sensor signals at low frequencies. This is due to the capacitance characteristics of the film [10][11]. The capacitance of PVDF is a function of its geometry, indicating that the cutoff frequency is usually determined by the amplifier input impedance alone \((f_c = 1/2\pi RC)\). For example, if an amplifier has an input impedance of 10k\(\Omega\) for a given PVDF capacitance of 3nF it yields a cutoff frequency of 5.3kHz which is unacceptable for this application. One goal is to amplify signals of very low frequency near the DC level. To achieve lower cutoff frequencies the input resistance of the amplifier must be increased. Consequently, a non-inverting JFET voltage follower with an input impedance of about 10 12 \(\Omega\) was chosen to enable measurements at very low frequencies. This produces a cutoff frequency of about 5.3x10^-5 Hz. The drawback to a non-inverting buffer is that input bias currents of the op-amp cause the amplifier to saturate. This condition can be alleviated by providing another high impedance path to ground (see Fig. 2). The value of \(R\) must be high enough to provide a cutoff frequency below the lowest frequency of interest. For example, to achieve a cutoff frequency of 10 Hz with a sensor that has a capacitance of 3nF would require a 5.3M\(\Omega\) resistor. For this example, \(R = 50 \text{ M}\(\Omega\) which results in a cutoff frequency of about 1 Hz which fits the required specifications. The impedance control resistor determines the input impedance of the buffer so this resistance should be chosen with knowledge of the physical characteristics of the sensors to be used with the system.

4 Fig. 1: High-level design of the signal conditioner

Because of the possibility of high voltage spikes from PVDF sensors, the design includes two zener diodes to regulate the input signal. Diodes should be chosen with breakdown voltages higher than the opamp supply voltage. For the prototype amplifier, zener diodes with a 20V breakdown voltage were selected. G-force amplitudes and corrupting frequencies have been a concern. Therefore it was decided to have a selectable frequency range via switches on the circuit board. A range of high-pass and low-pass filters in a cascade arrangement was decided upon, each having the ability to be independently activated. The low-pass cutoff frequencies were 100 Hz, 500 Hz, 1 kHz, and 10 kHz. The high-pass cutoffs were 3Hz, 100 Hz, 500 Hz, and 1 kHz. With this design the user may select 15 combinations of high-pass and low-pass filters. An "allpass" switch has been included in both filter banks as a bypass. The LF347 op-amp was chosen because it has several useful features, e.g., extremely high input impedance (10 12 \(\Omega\)), low input bias current (50 pA), and wide bandwidth (4 MHz).

5 Input

Several active filter models were investigated, but after reviewing the tradeoffs, the Sallen-Key configuration was most suitable [12][13][14]. The highfrequency specification for this system is 10 kHz, which is well below the 1 MHz level at which this filter begins to degrade. Also, since the amplification is done in a separate circuit, all filter stages are unity gain, alleviating gain-bandwidth product issues. Filter selectivity is certainly an important factor but linear phase response is also significant, so only two filter families were explored i.e., Butterworth and Bessel. The Butterworth has a much steeper roll-off than the Bessel, but the phase response is not as flat. However, Bessel filters have such a gradual roll-off that the required order becomes prohibitive. Also, as shown in Fig. 4, the phase response of the Butterworth is nearly linear in the passband, translating into an acceptable group delay. Further examination of the delay shows us that it has little effect on the output of the filters. The delay is uniform through the majority of the pass-band-up approximately 4 kHz for 4th order. This was verified by comparing the total harmonic distortion of these two filters at frequencies near the cutoff. For 5 kHz, 9 kHz, and 10 kHz input signals the THD of both filter types is less than 0.006%. For these reasons the Butterworth was chosen. (1) (2) Each filter used in this project comprises two cascaded 2-pole filters, yielding a 4-pole configuration with all filters designed to have less than 0.5 dB attenuation in the pass-band.

Fig. 4 illustrates the layouts of the high-pass and low-pass 4-pole Sallen-Key filters. Values for all resistive and capacitive components are shown in table 2. Because the input to the high-pass filters is linked directly to the impedance control circuit, this is the optimum place to remove any DC offset, which may be present in the input. For this reason a low voltage DC offset adjustment was added to the non-inverting terminal of the summing amplifier (Fig. 4). This circuit allows any small op-amp bias voltages to be removed from the output of the summing amplifier before proceeding to the gain control, and possibly corrupting the output. The low-pass filter selection circuitry is nearly identical to that of the high-pass block. The only...
reduced cost. Its versatility makes it suitable for use with most PVDF sensors. This work was initiated from a simple output indicator. This amplifier is an excellent alternative to comparable designs but at a significantly lower cost. The precision of the system has proven to be useful, inexpensive, and relatively easy to fabricate. It also provides reliable and repeatable results for several PVDF sensor models. With the output connected to an analog-to-digital converter system, the test arrangement was composed of the amplifier, a Keithley data acquisition board, and a computer running National Instruments’ Lab VIEW software.

A visual display was added to the amplifier to alert the user of the presence of excessive g-forces. This simple circuit eliminates the need to use an oscilloscope to view the output when portability is an issue. The method chosen to accomplish this task was the illumination of three LEDs. Yellow, green, and red LEDs illuminate when the magnitude of the amplifier’s output reaches a peak value of one, seven, and ten volts respectively. Two sets of LEDs were used to indicate positive and negative g-forces. The circuit is illustrated in Fig. 8. The input is isolated by using an op-amp buffer to assure that the rectifier circuit does not interfere or load the output. It should be noted that the output of the rectifier circuit is not exactly equal to the peak AC value of the input due to the approximate 0.6V drop over the diode. This drop must be accounted for when designing the comparator circuit that lights the LEDs. The visual display circuits compare the DC voltage from the rectifier circuit with a predetermined threshold voltage. Operational amplifiers were employed here as well for design simplicity and to reduce component count.

Multiple mechanical frequencies must be utilized to test the accuracy of the filters and the sensitivity of the amplifier. To achieve clean consistent vibration signals, an aluminum cantilever beam was used to create vibrations and accelerations of varying amplitude and frequency (see Fig. 7). Testing of low frequencies was accomplished using the cantilever beam, while high-frequency testing was completed using an electrodynamic shaker.

To analyze the functionality of the amplifier in a time-efficient manner, the output of the sensors was read through a data acquisition system for comparative purposes. This test arrangement was composed of the amplifier, a Keithley data acquisition board, and a computer running National Instruments’ Lab VIEW software.

As with most signal amplifiers, linearity is a significant factor in this design, therefore two tests were employed to verify the efficacy of each stage. Initially, the amplifier was set to 1X gain with all filters bypassed. The input voltage was incrementally increased from 0V to 10V while recording the outputs and calculating the respective correlation coefficients. The test was repeated with one high-pass and one low-pass filter activated to validate the filter circuits. The process was then repeated for numerous combinations being careful not to saturate each stage. The worst-case deviation from linearity is illustrated in Fig. 10. With a 1X gain selected, the upper 3dB point of the amplifier is 220 kHz. With the gain set at 166X, the 3dB point is shifted to 18 kHz, reducing the operating bandwidth as expected, but still remaining within the design limits. The 3dB point for each filter was within 5% of the calculated value, and the roll-off rates exceeded 65 dB/decade. In order to scale the output correctly the gain values must be accurately known, otherwise significant errors will result when calculating the acceleration or vibration magnitudes. All five gain switches were toggled to determine the influence of each. The results are summarized in table 3. Small deviations from the predicted values can be attributed to component variations but are still within design limits. All goals of table 1 were accomplished or exceeded.

An alternative technique for analyzing signals from PVDF sensors has been introduced and this signal conditioning system has proven to be useful, inexpensive, and relatively easy to fabricate. It also provides reliable and repeatable results for several PVDF sensor models. With the output connected to an analog-to-digital converter card the signal processor described here exceeded the capabilities of similar products tested. This conditioner adds several useful features to comparable products such as a selectable gain, high-pass and low-pass filters, and a simple output indicator. This amplifier is an excellent alternative to comparable designs but at a significantly reduced cost. Its versatility makes it suitable for use with most PVDF sensors. This work was initiated from
an industrial need for a simple and reliable acceleration and vibration signal conditioning system for automated
integrated circuit placement, still there can be many other uses, e.g., impact sensors, flow meters, contact
microphones, etc. Several sensors can be connected to similar conditioners, and by simultaneously monitoring
the outputs of two or more devices, one can gain a better understanding of where vibrations are originating.

Figure 1: Fig. 2:

Figure 2: Fig. 3:
Figure 3: Fig. 4:

Figure 4: Fig. 5: Fig. 6:
Figure 5: Fig. 8:

Figure 6: Fig. 10:
Parameter Specification

Frequency Range: 0 Hz to 10 kHz, at selectable ranges
Filter roll-off: 60 dB/decade
THD: <0.02%
Linearity: <0.2% deviation
Resolution: 1.0 µg/Hz
Gain: Selectable up to 150
Thermal Stability: Minimal effect
Dynamic Range: ±50 g
Transverse Sensitivity: <1%
Output: +/-10V

II.

Table 1:

| Freq. | R1   | R2   | R3   | R4   | C1   | C2   | C3   | C4   |
|-------|------|------|------|------|------|------|------|------|
| Low- 100 Hz | 2.32 kΩ | 21.2 kΩ | 18.2 kΩ | 18.9 kΩ | 1.0 nF | 3.3 nF | 470 pF | 10 nF |
| Pass 500 Hz | 1.66 kΩ | 16.3 kΩ | 2.33 kΩ | 19.0 kΩ | 6.8 nF | 22 nF | 3.3 nF | 22 nF |
| 1 kHz | 2.18 kΩ | 18.4 kΩ | 1.59 kΩ | 17.2 kΩ | 22 nF | 68 nF | 10 nF | 220 nF |
| 10 kHz | 8.93 kΩ | 37.5 kΩ | 3.55 kΩ | 18.9 kΩ | 20 nF | 220 nF | 100 nF | 220 nF |
| High-3 Hz | 17.6 kΩ | 15.0 kΩ | 42.4 kΩ | 6.21 kΩ | 3.3 µF | 3.3 µF | 3.3 µF | 3.3 µF |
| Pass 100 Hz | 15.5 kΩ | 11.3 kΩ | 26.6 kΩ | 3.89 kΩ | 220 nF | 100 nF | 220 nF | 220 nF |
| 500 Hz | 4.85 kΩ | 4.14 kΩ | 14.5 kΩ | 2.04 kΩ | 100 nF | 100 nF | 100 nF | 68 nF |
| 1 kHz | 2.43 kΩ | 2.07 kΩ | 16.2 kΩ | 1.40 kΩ | 100 nF | 100 nF | 100 nF | 22 nF |

Figure 7: Table 1

Table 2:

| Vin | Vout | Gain | Actual Gain | %error |
|-----|------|------|-------------|--------|
| 1.525 | 1.55 | 1 | 1.016 | 3.25% |
| 0.31 | 1.575 | 5 | 5.081 | 1.59% |
| 0.135 | 1.375 | 10 | 10.18 | 1.82% |
| 0.105 | 5.2 | 50 | 49.52 | -0.96% |
| 0.0525 | 5.1 | 100 | 97.14 | -2.94% |
| 0.052 | 8.625 | 166 | 165.8 | -0.08% |

Figure 8: Table 2

Table 3:

Figure 9: Table 3
| Parameter               | Measured Results                  |
|-------------------------|-----------------------------------|
| Frequency Range         | 0 Hz to 10 kHz, at selectable ranges |
| Filter roll-off         | >65 dB/decade                      |
| THD                     | <0.012%                            |
| Linearity               | 0.11% deviation                    |
| Resolution              | 0.04 µ g / Hz                      |
|                         | in conjunction with sensor         |
| Gain                    | Selectable up to 166               |
| Thermal Stability       | Minimal effect                     |
| Dynamic Range           | > 50 g                             |
| Transverse Sensitivity  | < 1%                               |
| Output                  | +/-10V                              |

Figure 10: Table 4:
