TP294

ACCELEROMETER FOR HIGH FREQUENCY, LOW NOISE APPLICATION, WITH SELF TEST/ID FEATURE

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Mr. Fernando Gen-Kuong holds a BS and MS degrees in Electrical Engineering from the University of California, Los Angeles, and is currently obtaining his MBA degree at the University of California, Irvine. Mr. Gen-Kuong has been working for Endevco Corporation, for 6 years designing hybrid electronics for piezo-electric accelerometers, analog and digital application specific integrated circuits (ASICs), and microprocessor based signal conditioners with digital tracking filter capabilities. Mr. Gen-Kuong is a member of the Institute of Electrical and Electronics Engineers (IEEE).

Abstract

Endevco has been involved in the development and manufacture of accelerometers for high frequency, low noise environments, particularly in marine applications. The design and selection of an accelerometer for such applications involves multiple trade offs between many denominators. Among the key factors are output sensitivity, frequency response, size, connectors and cabling, shear or compression sensing mode, use of integral electronics with special features such as self test and I.D., residual noise, EMI rejection, mounting arrangements, and costs.

This paper reviews the many issues facing the designer and user of accelerometers for high sensitivity, low noise, micro g applications. This paper also presents recent experimental data on noise performance of accelerometers used in such applications and examines alternative noise measurement techniques and their relative merits.

I. INTRODUCTION

Piezoelectric accelerometers are very simple and reliable devices. Perhaps their largest drawback is their high impedance characteristics. Electrically they are equivalent to a small capacitor, typically a few hundred picofarads, in series with a voltage generator, or alternatively, in parallel with a charge generator. This high impedance necessitates the use of shielded cables with special construction to avoid tribo-electric noise arising from movement of the cable.

When environmental conditions allow, high output impedance problems may be avoided by building signal conditioning circuitry into the accelerometer. Accelerometers with internal electronics are widely used and available from many manufacturers.

While internal signal conditioning solves the problems associated with high impedance, there still is room for improvement in overall system reliability. Marine silencing vibration measurements require monitoring accelerations at hundreds of points throughout the hull. Some of the accelerometers are installed during the build up of the hull structure and become virtually inaccessible. Thousands of feet of cable may be required to connect the accelerometers to the central data collector.

In order to make accurate, reliable measurements with a large number of widely located accelerometers, it is essential to know with certainty which accelerometer is connected to a particular cable, that the cable is indeed connected, free of short or open circuits, and that the accelerometers and cables are functioning correctly together. The Endevco Corporation 35427F accelerometer was designed to eliminate these problems by generating a test signal and unique identification code upon command.

The 35427F accelerometer was specifically designed for submarine vibration monitoring, though submarines are not the only naval system for which noise plays a vital role. Sounds radiated by surface ships reveal their presence to enemy submarines. A modern submarine proceeding at slow speed produces on the order of 10 mW acoustic power, while surface ships generally radiate from 5 to 100 Watts. A quiet running submarine or surface ship requires identifying and reducing internal noise sources. The noise sources may be identified by correlating hull vibrations with the vibration of machinery in the vessel that are potential sources of noise. In as much as the ultimate goal is to reduce the hull noise to the minimum, the accelerometer itself must have the lowest possible noise floor. Therefore the 35427F was constrained to have high sensitivity with low noise.

II. THE ACCELEROMETER

In order to provide the lowest profile accelerometer for mounting on machinery in confined spaces, and a design that would permit 360° cable orientation during mounting, the annular shear design approach was selected over a compression design. The Endevco 35427F accelerometer is a double shielded, annular ring shear design. All circuitry is incorporated in a single hybrid microcircuit on an annular substrate mounted on the seismic mass. A schematic cross section of the accelerometer is shown in Figure 1. The annular shear design provides low pyroelectric and base strain sensitivities in a small size. The annular design allows for a mounting hole through the center of the acclerometer so that it may be attached with a single screw with the side cable oriented in any direction. Double shielding and the low output impedance of the signal conditioning circuitry provide low susceptability to electromagnetic interference. The inner shield of the accelerometer is connected to the inner shield of the triaxial cable which serves as the ground return for the circuit. The accelerometer case provides the outer shield. An integrally attached cable eliminates the potential problem of loose or contaminated connector sets. Also, the side attached cable provides a lower overall profile than a top mounted cable assembly. This reduces potential cable damage which is typical of top mounted cable assemblies. The polyurethane jacketed cable is constructed of materials to meet flame, smoke, and toxicity requirements. The cable features a Kevlar reinforcement braid to withstand installation tensile loads.

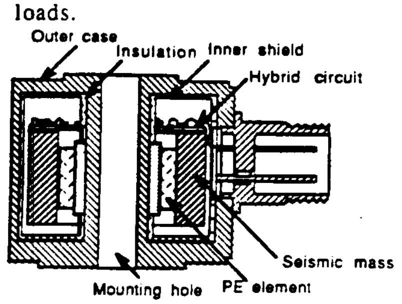


Figure 1. Simplified cross-section of the Endevco 35427F accelerometer. The inner shield is insulated from the case

III. HYBRID MICROCIRCUIT

The internal electronic circutry of the 35427F provides the following features and benefits:

1) charge to voltage conversion,
2) Transmission of vibration output signal on the same two wires that carry the supply current from the external power supply,
3) self test,
4) identification,
5) low output impedance,
6) immunity to current supply variations,
7) reduced susceptibility to EMI,
8) low noise,
9) gain calibration,
10) high frequency response compensation.

In self test mode the hybrid microcircuit provides a voltage output test signal used to check the electrical integrity of the sensing element together with the internal signal conditioner electronics, connections, and cables. After transmission of the test signal, six (6) octal digits with an odd parity bit are transmitted to identify the sensor. Figure 2 shows the waveforms of the self test and identification signals.

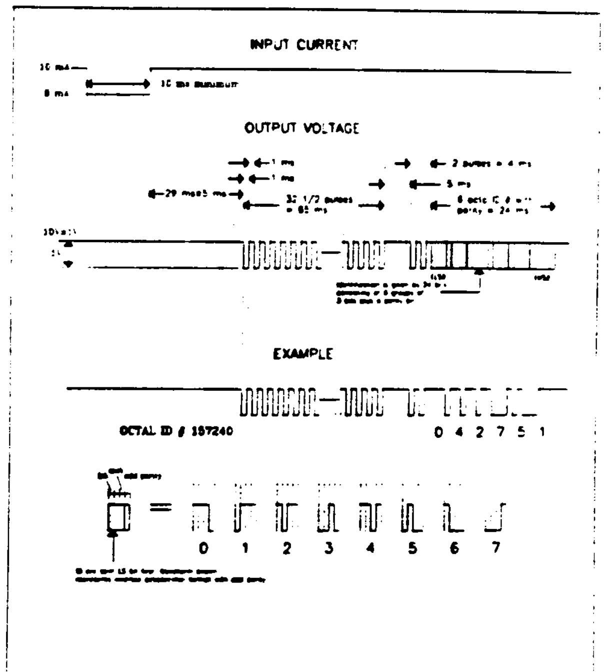


Figure 2. Timing Diagram

Figure 3 shows a block diagram of the circuitry. The circuitry contains an analog and a digital section, each with its own application specific integrated circuit (ASIC). The analog functions are handled by a bipolar ASIC for low noise and high frequency performance, while the digital functions are handled by a CMOS ASIC for low power consumption performance and minimum size.

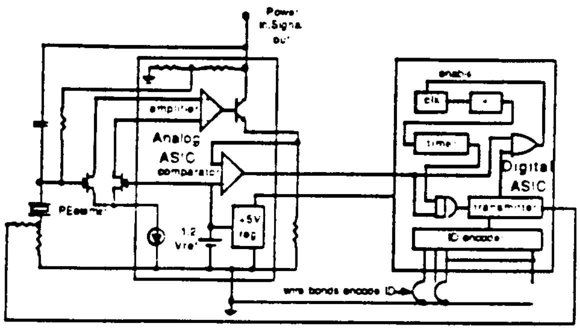


Figure 3. Simplified block diagram of the Endevco 35427F accelerometer. An external dual JFET is used for the first stage of the signal conditioner to provide low noise. The self-test/ID signal is injected in series with the PE element so the entire signal chain will be checked.

Analog Section

The analog ASIC incorporates an amplifier, for the charge converter; a band-gap voltage reference for dc bias temperature stability; a +5 Vdc voltage regulator to supply power to the digital ASIC; a comparator to detect a threshold crossing of the dc supply current and trigger the digital ASIC. To provide the lowest possible noise, the first stage of the charge converter uses an external discrete, low-noise, dual JFET. The bias current for the JFET stage is provided by current sources in the analog ASIC. This provides improved power supply rejection performance.

Digital Section

The digital ASIC incorporates a power-on-reset for proper start-up operation; a clock oscillator and divider chain to control timer and transmission; a timer to measure trigger pulse width and disregard glitches; and an ID encoder to add odd parity bit to the six octal numbers and serially transmit them after the transmission of the test signal. The clock oscillator is shut-off completely when the accelerometer is operating in its normal mode to ensure that digital switching noise will not corrupt the acceleration signal. The ID number is coded into the hybrid microcircuit by 18 wire bonds, which provide a total of up to 262,144 discrete ID numbers.

Operation Description

In normal operation the 35427F accelerometer operates just like any other accelerometer with internal signal conditioning electronics. In test mode the 35427F continues to provide vibration information while transmitting the test signal and ID number.

A request for self test/identification operation is made by reducing the supply current to the 35427F accelerometer from 10mA to below 8mA for a specified minimum amount of time. Transmission will start whenever the supply current goes back to 10mA after staying low for the specified minimum time. Transmission will end approximately 128ms after the supply current has returned to 10mA. After transmission starts, any further requests for transmissions will be disregarded until transmission ends. DC supply current, threshold level, and transmission duration can be modified within some limitations to meet specific requirements.

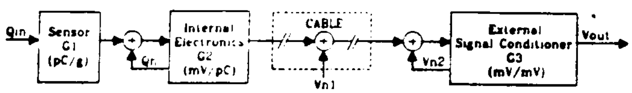
IV. NOISE PERFORMANCE

Noise measurements using 1/3 octave filters was established by Gen-Rad, and is still widely used today. A 1/3 octave analyzer uses bandpass filters whose bandwidth are 50% of the center frequency are called constant percentage bandwidth filters or constant Q bandpass filters. For example, a noise measurement at 100 Hz is done by using a filter with a 50 Hz bandwidth. In high frequency applications this may not be desireable since a measurment at 5 kHz will be done by using a 2.5 kHz bandwidth bandpass filter.

A 5 kHz, 1/3 octave measurement will not be able to identify noise sources mixed in a 5 kHz signal if they are located between 3.75 kHz and 6.25 kHz. A narrowband constant bandwidth bandpass filter will give more accurate measurements, and a detailed spectral distribution will be able to better identify dominant sources of noise. Narrowband spectral analysis is a potent tool in diagnostic studies.

To detect low level signals the inherent noise of the measuring instrumentation must be as low as possible, but it must also be properly configured.

Figure 4 shows a block diagram of an accelerometer measuring system consisting of the sensing element, the internal electronics, cabling, and the external signal conditioner. To maximize the signal to noise ratio of the system, most of the amplification should be done at the input stages - ideally at the sensing element. This minimizes the noise contributions from external sources, and the external signal conditioner is not required to have very low noise characteristics.



$$Vout = Vaccel + VonT$$

$$Vaccel = Qin \cdot G1 \cdot G2 \cdot G3$$
$$VonT = (Von1^2 + Von2^2 + Von3^2)^{1/2}$$

$$Von1 = Qn \cdot G2 \cdot G3$$
$$Von2 = Vn1 \cdot G3$$
$$Von3 = Vn2 \cdot G3$$

To maximize signal to noise ratio

$G1 > G2 > G3$
Qn and Vn2 as small as possible
(Vn2 does not need to be as small as Qn)
Low susceptibility to external interferences to minimize Vn1

Figure 4. Block Diagram of Typical Vibration Measuring System.

Table 1 shows a number of ways that a measuring system with an overall gain of 1000mV/g could be configured. Note that the lowest total rms voltage output noise is achieved when all the gain is set at the front end.

Case 8 and 9 both have G1 = 100, but case 8 has G2=1 and G3=10, while case 9 has G2=10 and G3=1. Case 9 is 1.71 times less noisier than case 8 by having higher gain at the front end.

The other advantage of having higher gain at the front end is the decreased sensitivity to Vn1 and Vn2 noise sources. This can be seen in Table 2 cases 2 and 4 where Vn1 and Vn2 were increased to 5uV rms. In cases 3 and 4 gain configuration, the noise increased from 10.10uV rms to 12.25uV rms (1.21 times); but in cases 1 and 2 gain configuration, the noise increased much more from 17.32uV rms to 71.41uV rms (4.12 times)

The crystal sensitivity used in Endevco Corporation model 35427F is approximately 40 pC/g, and the gain of the internal charge converter is approximately 2.5 mV/pC, thus giving a total sensor sensitivity of 100 mV/g. The rms output voltage noise was measured to be less than 12uV rms (an equivalent Qn=0.005pC rms with respect to the charge converter input, or 120ug with respect to the mechanical vibration input).

Some of the trade-offs of using a high sensitivity crystal are higher cost and reduced frequency response (lower resonant frequency).

TABLE 1

	GT (mV/g)	G1 (pC/g)	G2 (mV/pC)	G3 (V/V)	Qn (pC rms)	Vn1 (uV rms)	Vn2 (uV rms)	Von1 (uV rms)	Von2 (uV rms)	Von3 (uV rms)	VonT (uV rms)
1	1000	1	10	100	0.001	1.00	1.00	1000.00	100.00	100.00	1009.95
2	1000	1	100	10	0.001	1.00	1.00	1000.00	10.00	10.00	1000.10
3	1000	1	1000	1	0.001	1.00	1.00	1000.00	1.00	1.00	1000.00
4	1000	10	10	10	0.001	1.00	1.00	100.00	10.00	10.00	101.00
5	1000	10	100	1	0.001	1.00	1.00	100.00	1.00	1.00	100.01
6	1000	50	2	10	0.001	1.00	1.00	20.00	10.00	10.00	24.49
7	1000	50	10	2	0.001	1.00	1.00	20.00	2.00	2.00	20.20
8	1000	100	1	10	0.001	1.00	1.00	10.00	10.00	10.00	17.32
9	1000	100	10	1	0.001	1.00	1.00	10.00	1.00	1.00	10.10
10	1000	1000	1	1	0.001	1.00	1.00	1.00	1.00	1.00	1.73

TABLE 2

	GT (mV/g)	G1 (pC/g)	G2 (mV/pC)	G3 (V/V)	Qn (pC rms)	Vn1 (uV rms)	Vn2 (uV rms)	Von1 (uV rms)	Von2 (uV rms)	Von3 (uV rms)	VonT (uV rms)
1	1000	100	1	10	0.001	1.00	1.00	10.00	10.00	10.00	17.32
2	1000	100	1	10	0.001	5.00	5.00	10.00	50.00	50.00	71.41
3	1000	100	10	1	0.001	1.00	1.00	10.00	1.00	1.00	10.10
4	1000	100	10	1	0.001	5.00	5.00	10.00	5.00	5.00	12.25

V. ENDEVCO 35427F PERFORMANCE SPECIFICATION

The specifications of the ENDEVCO 35427F accelerometer are summarized in Table 3.

TABLE 3

Linear range	±10 g minimum
Dynamic range	>100 dB
Sensitivity	100 mV/g ±5%
Frequency response	±10% from 5 Hz to 10 kHz
Resonant frequency	25 kHz minimum
Amplitude linearity	< ±1% of reading to ±10 g
Phase dispersion	±1.5° of specified curve from 5 Hz to 2 kHz
Transverse sensitivity	<3% in any transverse direction
Temperature response	Typically ±3% from +5 to 55°C
Self-test	Per fig. 2
Power requirement	10 mA constant current. 7 mA to request self-test/ID
Output impedance	<25 Ω
Residual Noise	<1 micro g at 1 Hz bandwidth over frequency band of 10 Hz to 10kHz, except for 60 Hz or any harmonics of 60 HZ. 1/3 Octave: <33 Micro g RMS. 10Hz to 1kHz.
Diameter	.98" exclusive of cable
Height	.86" exclusive of mounting screw

NOTE: Sensitivity can be increased to 5000 mV/g without increasing input noise. Frequency response can be extended to 20 kHz by changing low pass filter.

VI. CONCLUSIONS

Measurement groups are concerned that much of the test data that has been collected over the years at enormous expense is of dubious quality. This concern comes from the possibility that the sensors were not working properly or were not properly connected. Self test/ID circuitry build into accelerometers can eliminate these doubts.

The Endevco 35427F accelerometer was designed specifically to measure vibration in confined mounting spaces on submarines, but clearly would be useful in applications, wherever large number of accelerometers are involved.

There are of course, limitations on what should be expected from a self test/ID signal. It does not constitute a true calibration. That would require the whole accelerometer to be vibrated at a known acceleration. Nevertheless, the repetitive appearance of a self test signal of the correct frequency and amplitude provides very high assurance that the accelerometer and cabling are operating correctly.

The term "Smart Sensor" is rather vague. Some regard any sensor with internal signal conditioning as smart; others regard only sensors with internal microprocessors as smart. Whether or not an accelerometer with self test/ID capability is regarded as smart, it can serve to greatly increase the assurance that vibration data are in fact correct and accurate.

Over the years accelerometer residual noise specifications have been typically specified as broadband or 1/3 octave. In recent years, emphasis in noise measurements has increasingly been place on narrowband spectra. There are several reasons for this trend. Most important is the fact that its detailed spectral distribution is a most important clue as to the nature of the noise source.