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The Endevco® High-g Shock Triaxial Accelerometer: a Smaller, More Cost-effective Solution to Making Triaxial Measurements

Technical Paper 334

By Randy Martin

The ENDEVCO® high-g shock triaxial accelerometer: A smaller, more cost-effective solution to making triaxial measurements

In alignment with this year's theme of "Next Generation Fuzing for Next Generation Weapons," Meggitt Sensing Systems discusses the new Endevco® high-g shock triaxial accelerometer. This new accelerometer is a triaxial version of the industry standard Endevco® single-axis undamped high-g shock accelerometer. Having the same footprint and bolt-pattern, the new triaxial accelerometer is a drop-in replacement for the single-axis unit in most installations. Current fuze and data recorder designs may make a triaxial measurement using three single-axis accelerometers and a triaxial mounting block. The new triaxial accelerometer will make the same measurement in a much smaller envelope for approximately two-thirds the cost. Also coming soon to the Endevco® high-g shock product family is a lightly damped version of the triaxial accelerometer, which will offer more survivability and reliability in unpredictable and harsh environments. With the realized space savings one could even imagine using both the undamped and damped configurations in a single design where the undamped triaxial sensor will capture high bandwidth data and the damped triaxial sensor will offer more survivability and reliability in the increasingly harsh environments of today's weapon systems.

Introduction

It is not uncommon for advanced penetrator weapon systems to require the triaxial measurement of mechanical shock. Whether the measurement is made within the fuze itself or within a fuzewell data recorder, the requirement is the same; an accelerometer that will survive the often unpredictable harsh environment of the penetration event while recording reliable acceleration data. Current fuze and data recorder designs that require a triaxial measurement may use three single-axis high-g shock accelerometers with a custom machined triaxial mounting block. The size of the next generation fuzes and data recorders is shrinking so there is a need to make the same triaxial measurement within a smaller envelope dimension. In addition to reduced size, the next generation also demands lower cost and more reliability as compared to the past technology. In alignment with this year's theme of "Next Generation Fuzing for Next Generation Weapons," Meggitt Sensing Systems discusses the new Endevco® model 7274 high-g shock triaxial accelerometer.

The model 7274 is essentially a triaxial version of the industry standard Endevco® model 7270A undamped, high-g shock accelerometer. It has an integral eight conductor cable and is available in ranges of 2,000 g, 6,000 g, 20,000 g and 60,000 g. Having the same footprint and bolt-pattern (and approximately twice the height), the new triaxial accelerometer is a drop-in replacement for the single-axis unit in most installations. And since the 7274 uses the same undamped microelectromechanical (MEMS) sensing element as the 7270A (which has been in service for over 30 years), it will make the same measurement in a much smaller envelope for approximately two-thirds the cost. The relative size of the two accelerometers is shown in Figure 1. In general terms the width and length of the two versions are essentially the same, while the height of the triaxial package is approximately twice that of the single-axis package.

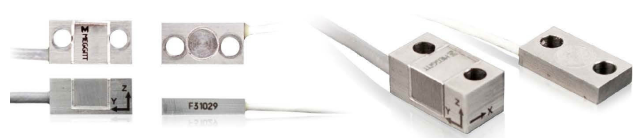

Figure 1: Relative size of the triaxial and single-axis high-g shock accelerometers (photo not to scale).

Since the 7274 uses the same undamped sensing element as the 7270A, many of the performance characteristics will be the same. This paper will focus on the performance parameters that are specific to the unique triaxial arrangement of the sensing elements within the package. Discussion topics include transverse sensitivity, shock survivability and overrange, and base strain sensitivity. Additionally certain details relating to the proper usage of the new triaxial accelerometer will be discussed.
The accelerometers discussed in this paper are controlled under the International Traffic in Arms (ITAR) regulations. Because this paper is intended for public release it can only contain non-technical data as defined under the ITAR, therefore the amount of information presented must be limited. Additional details can be released to properly screened individuals in industry, academics or government upon request.

Transverse Sensitivity

Transverse sensitivity, also referred to as cross-axis sensitivity or crosstalk, is the sensitivity of an accelerometer to a stimulus in a direction that is perpendicular to the primary sensing axis (or sensitive axis). Often expressed as a percentage of the axial sensitivity, a common specification for this parameter is five percent maximum. Although some level of transverse sensitivity could be inherent in the MEMS sensing element itself, the main contributing factors will be the flatness and parallelism tolerances of the subcomponents and accelerometer assembly. This parameter, along with other key accelerometer specifications, is explained in more detail in a technical paper published by Meggitt Sensing Systems [1]. For a triaxial accelerometer it is a little easier to visualize transverse sensitivity. For a shock input to the z-axis of the accelerometer, the output you can expect to see in the x and y-axes represents an error and will depend on the transverse sensitivity.

One common method for measuring the transverse sensitivity of an accelerometer is by using a specialized vibratory shaker designed for this purpose. The unit-under-test (UUT) is mounted on the shaker so that the sensitive axis is aligned with the axis of vibration and the sensitivity is recorded. Next the UUT is reoriented so that the sensitive axis is now orthogonal to the direction of vibration. While being vibrated, the UUT is rotated 360 degrees (the sensitive axis remains orthogonal to the direction of vibration) and the maximum transverse sensitivity is recorded. This method, due to the low vibration levels, is typically only effective for lower ranged units that have higher sensitivities. For this reason this measurement is made on a 7274 triaxial accelerometer with a 2,000 g range (the lowest available). The measured transverse sensitivities are 1.1 percent and 0.6 percent for the y and z-axis, respectively (mounting limitations prevented testing the x-axis on this shaker).

For the purpose of illustration, an alternate method to show transverse sensitivity is pursued. The model 2911 vibration standard-shaker, a part of the Endevco® Automated Accelerometer Calibration System (AACS), is shown in Figure 2. This shaker allows for more flexibility in vibration amplitude and frequency; however it is not optimized for testing transverse sensitivity. The data sheet for the 2911 shaker specifies 5% maximum transverse motion up to 10 kHz with a balanced load [2].

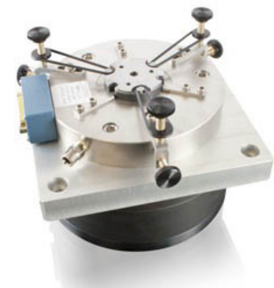

Figure 2: Photograph of the Endevco® Model 2911 vibration standard-shaker.

The plots in Figures 3 through 5 show the results of testing in all three axes of a 7274-60K triaxial accelerometer. One would expect the true transverse sensitivity to be in phase with the test frequency, so it is very much possible that the transverse motion of the shaker itself is contributing to the measurements made below. The take-away here is that the transverse sensitivity of the 7274 is no worse than what is presented below while all values shown below are less than five percent.

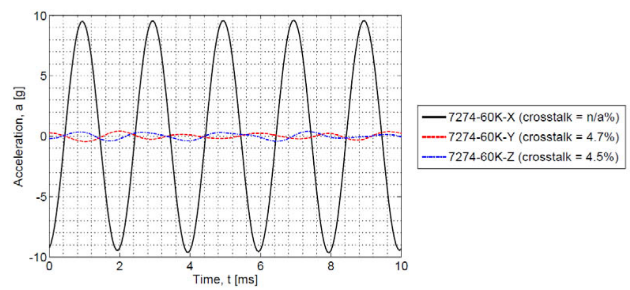

Figure 3: Transverse sensitivity measurement for the 7274 tested on the 2911 shaker in the x-axis.

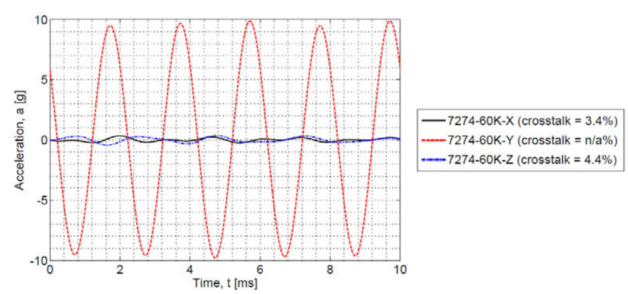

Figure 4: Transverse sensitivity measurement for the 7274 tested on the 2911 shaker in the y-axis.

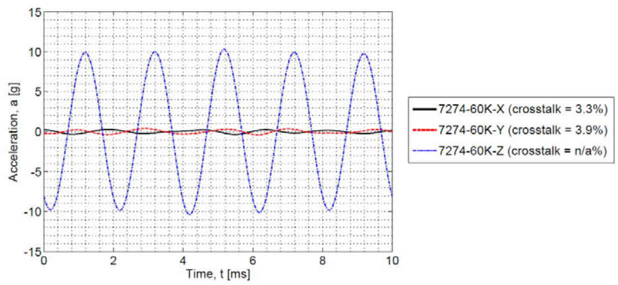

Figure 5: Transverse sensitivity measurement for the 7274 tested on the 2911 shaker in the z-axis.

Low g shock testing

At Meggitt Sensing Systems, shock calibration on high-g shock accelerometers is performed on the model 2925 Comparison Shock Calibrator (POP) which is a part of the Endevco® AACS [3]. A Pneumatically Operated Projectile (hence "POP") impacts an anvil where the unit-under-test (UUT) and reference accelerometer are mounted. Various anvil weights and pulse shaping methods allow for shock testing up to 10,000 g with haversine waveforms. To accommodate calibration of triaxial accelerometers custom test fixtures are required. The model 2974M8 triaxial calibration test fixture shown in Figure 6 is designed to properly align the origin of the triaxial coordinate system of the 7274 with the center of mass of the test fixture. The 2974M8 triaxial test fixture is available to support the laboratory testing or calibration of the model 7274.

Figure 6: Triaxial calibration fixture used on the 7274.

Figures 7 through 9 show shock tests performed on the 7274 using the POP in each of three axes. All three channels are recorded in order to show the low level of transverse sensitivity; the average transverse sensitivity recorded is 1.5 percent and the measured transverse sensitivities are reported in the caption of each figure. The ~22,000 Hz oscillation after the shock pulse shown in the plots below will show up on both the reference and UUT signals during a formal calibration and is an artifact of the POP. Since the calibration is performed by comparing peak values these oscillations will not affect the integrity of the calibration.

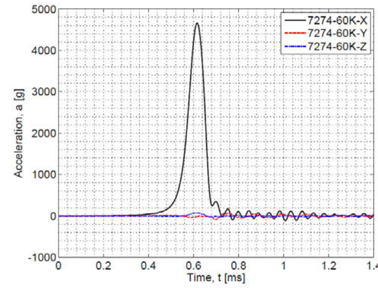

Figure 7: Plot showing a 4,661 g shock in the x-axis of the 7274; the measured transverse sensitivities for the x-axis and z-axis are 3.3 percent (186/5588*100) and 1.1 percent (62/5588*100), respectively.

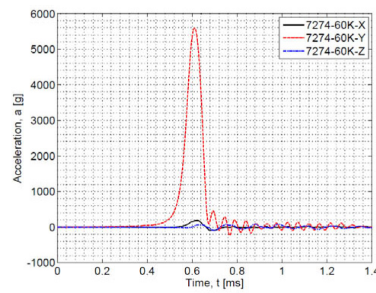

Figure 8: Plot showing a 5,588 g shock in the y-axis of the 7274; the measured transverse sensitivities for the y-axis and z-axis are 0.8 percent (38/4661*100) and 1.6 percent (73/4661*100), respectively.

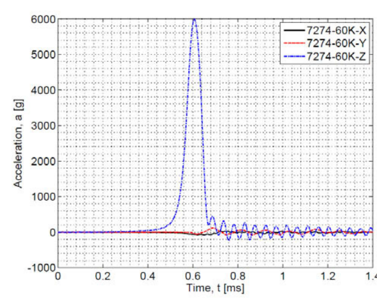

Figure 9: Plot showing a 5,987 g shock in the z-axis of the 7274; the measured transverse sensitivities for the x-axis and y-axis are 1.3 percent (76/5987*100) and 1.0 percent (58/5987*100), respectively.

High g shock testing and zero shift after shock

To test beyond the 10,000 g limit of the POP, the Endevco® model 2973A Hopkinson bar (an add-on to the AACS governed by the ITAR) is used. The time histories shown below were captured using the same triaxial test fixture used above (Figure 6). Since this test fixture is intended to be used as a calibration fixture at 5,000 g on POP, testing to 60,000 g on the Hopkinson bar really pushes the limits. For high-g shock testing, the fixture orientates the UUT and retains it on the Hopkinson bar during the test, but the sheer weight of the test fixture will have an influence on the shock pulse (which is not ideal for a high-g shock test fixture). Each production 7274 unit receives a shock on the Hopkinson bar at full scale range in the z-axis before the final calibration on the POP.

The results of Hopkinson bar testing at amplitudes approaching the full-scale range of the 7274-60K in each of three axes are presented in Figures 10 through 12. In each figure, both unfiltered and 50 kHz low-pass filtered data are shown for a single shock event. The multiple shock pulses shown in each shock event are the result of wave reflections within the Hopkinson bar when the unit is hard-mounted to the bar (a single shock pulse, if desired, could be obtained with the use of a breakaway). The values reported in each figure's legend are zero shift after shock measurements, where 'zs' is an abbreviation of 'zero shift.' The zero shift measurement is made within 30 seconds following the shock event.

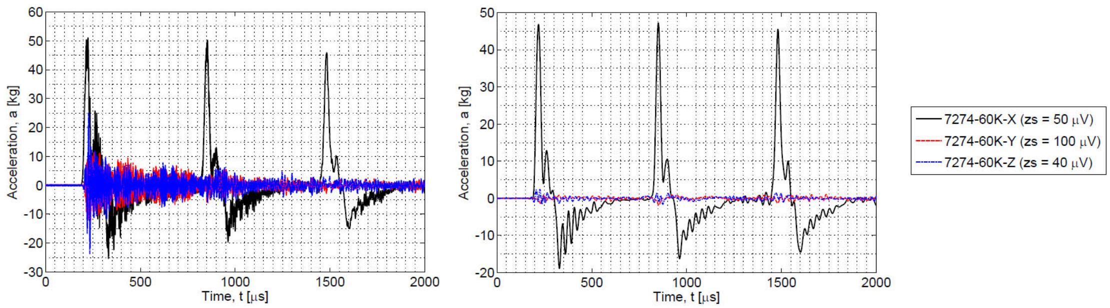

Figure 10: Hopkinson bar test in the x-axis of the 7274 near 50 kg: (a) unfiltered, (b) low-pass filtered at 50 kHz.

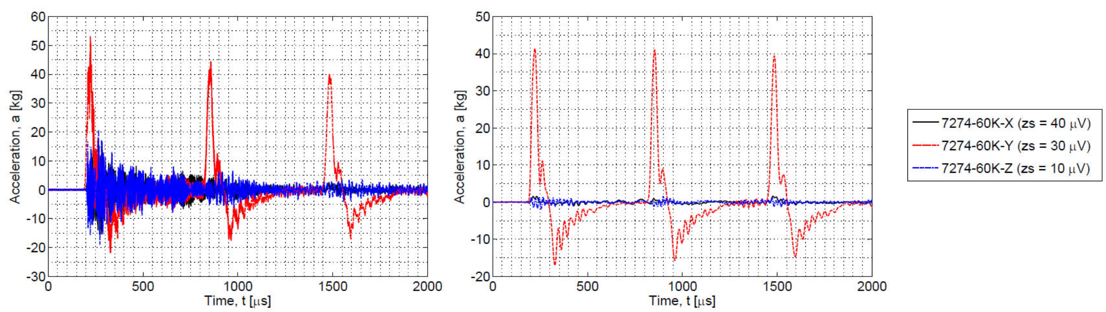

Figure 11: Hopkinson bar test in the y-axis of the 7274 near 40 kg: (a) unfiltered, (b) low-pass filtered at 50 kHz.

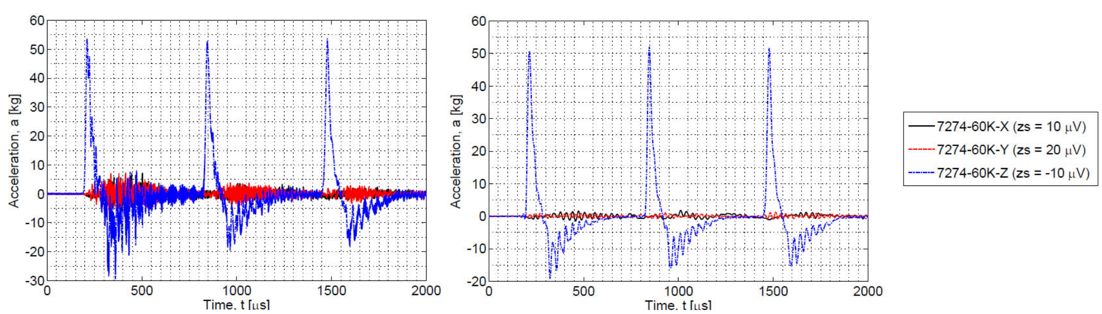

Figure 12: Hopkinson bar test in the z-axis of the 7274 near 50 kg: (a) unfiltered, (b) low-pass filtered at 50 kHz

Survivability testing to greater than 3x range

In order to perform further survivability testing, the 7274 triaxial accelerometer is now mounted directly to the Hopkinson bar (in the z-axis orientation) using a temporary adhesive at the mounting interface and the two mounting screws. The use of adhesive in combination with the mounting screws is further discussed in the USAGE AND HANDLING section below.

Figures 13 thru 15 show the representative time histories of Hopkinson bar testing of the 7274-60K at shock amplitudes up to 200,000 g in the z-axis. Just as before, unfiltered and filtered data is presented and the measured zero shift after shock values are reported in the figure legend. When comparing the time histories below to those acquired above (using the test fixture), you will notice that the resonant excitation is significantly reduced by eliminating the relatively large test fixture. Because slightly cleaner waveforms are obtained, values for transverse sensitivity are again reported for each test in the figure caption.

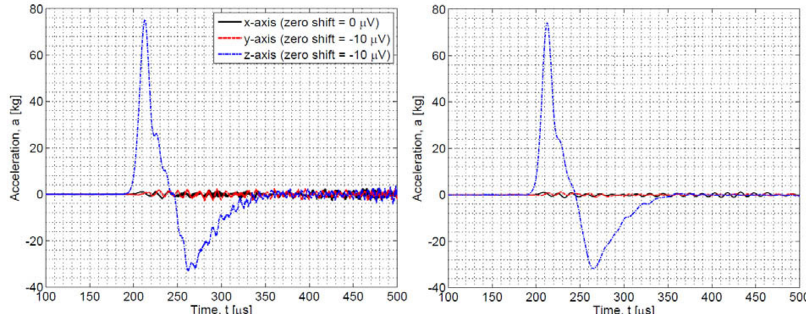

Figure 13: Hopkinson bar test in the z-axis of the 7274-60K at 74 kg: (a) unfiltered, (b) low-pass filtered at 80 kHz; the measured transverse sensitivity for both the x-axis and y-axis is 1.6 percent (1.2/74*100).

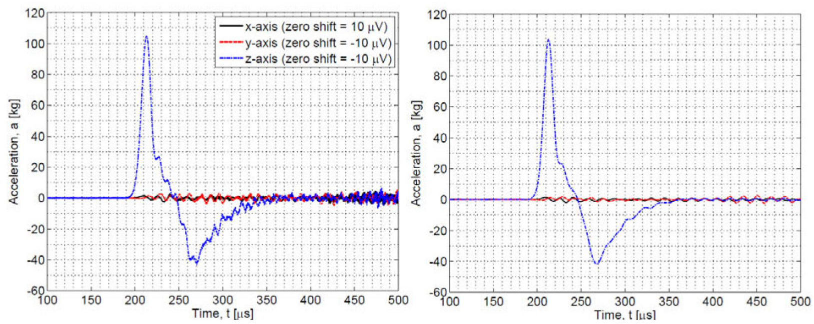

Figure 14: Hopkinson bar test in the z-axis of the 7274-60K at 104 kg: (a) unfiltered, (b) low-pass filtered at 80 kHz; the measured transverse sensitivities for the x-axis and y-axis are 1.4 percent (1.5/104*100) and 1.7 percent (1.8/104*100), respectively.

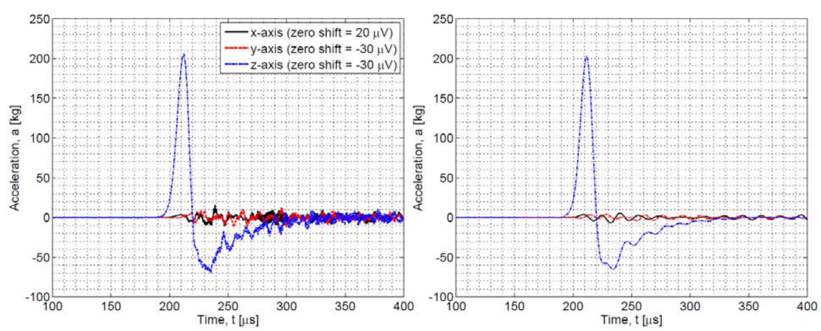

Figure 15: Hopkinson bar test in the z-axis of the 7274-60K at 202 kg: (a) unfiltered, (b) low-pass filtered at 80 kHz; the measured transverse sensitivities for the x-axis and y-axis are 1.8 percent (3.7/202*100) and 1.6 percent (3.3/202*100), respectively.

To obtain the higher shock amplitudes on the Hopkinson bar the current pulse shaping technique at the shock laboratory at Meggitt Sensing Systems results in much shorter pulse widths. It is assumed that longer pulse durations (with higher energy content) could cause more damage to the accelerometer, even with lower amplitudes. Future evaluation of the 7274 triaxial accelerometer will include testing in an environment that better simulates the intended application.to 200,000 g in the z-axis. Just as before, unfiltered and filtered data is presented and the measured zero shift after shock values are reported in the figure legend. When comparing the time histories below to those acquired above (using the test fixture), you will notice that the resonant excitation is significantly reduced by eliminating the relatively large test fixture. Because slightly cleaner waveforms are obtained, values for transverse sensitivity are again reported for each test in the figure caption.

Base strain sensitivity

In addition to transverse sensitivity, another error source for accelerometers is base strain sensitivity. Base strain sensitivity is basically the output from the accelerometer when subjected to a strain applied at its base (or mounting surface). Testing for base strain sensitivity is performed according to ISO 5347, paragraph 5.3.5 which employs a cantilever beam capable of applying 250 microstrain to the base of the UUT. Results are typically presented in either μV/V or equivalent g of output when tested at 250 microstrain.

The results of base strain sensitivity testing of the 7274-60K are shown in Table 1. Tests were performed in both the 'horizontal' and 'vertical' orientation, where the horizontal orientation puts the 7274's long edge along the width of the cantilever beam and the vertical orientation puts the 7274's long edge along the length of the cantilever beam.

Table 1: Base strain sensitivity testing of the 7274-60K.

	orientation	
axis	horizontal	vertical
X	4.17 μV/V = 13.9 equiv. g = .02% full scale	3.30 μV/V = 11.0 equiv. g = .02% full scale
Y	0.04 μV/V = .13 equiv. g = .00% full scale	0.81 μV/V = 2.7 equiv. g = .005% full scale
Z	1.86 μV/V = 6.2 equiv. g = .01% full scale	2.05 μV/V = 6.8 equiv. g = .01% full scale

Usage and handling

The handling of the 7274 high-g shock triaxial accelerometer will be very similar to that of the 7270A high-g shock single-axis accelerometer. Precautions should be taken to prevent inadvertent resonance excitation while handling the unmounted accelerometer; excessive resonant excitation could result in damage to the accelerometer. Additionally, since these devices are susceptible to electrostatic discharge (ESD), the same handling safeguards should be taken. The accelerometer should only be handled by properly grounded individuals at ESD safe work stations. ESD damage to an accelerometer will typically cause large shifts in the zero measurand output (ZMO) and/or result in a completely open leg of the Wheatstone bridge.

Similarly, due to the comparable package types, the recommended mounting procedures for the triaxial accelerometer are much like those for the single-axis accelerometer. First, it is important that the mounting surface is flat; uneven mounting surfaces will cause increased transverse sensitivity and unwanted static strain to the device. Next, due to the high levels of shock exposure, it is recommended to use an adhesive between the bottom surface of the accelerometer and the mounting surface. The adhesive will enhance the strength of the mounting screws and should not be used to replace the screws. Another purpose of using the adhesive in combination with the mounting screws is to minimize the effects of case dynamics on the data and to maximize the transmissibility of the shock input to the sensor. If it is decided that adhesive is not required in a specific application, it is recommended that an acoustic couplant be used instead in order to ensure that the accelerometer is in intimate contact with the mounting surface.

More specific usage and handling instructions will be given in the instruction manual shipped with the unit [4]. If for any reason the instruction manual is not included in the shipment, it can be requested by contacting the factory.

Applications

Since the model 7274 triaxial accelerometer shares the same footprint and bolt pattern as the 7270A single-axis accelerometer, it is a drop-in replacement in most applications. At roughly twice the height of the single-axis version, the triaxial accelerometer offers an approximate 90 percent reduction in envelope dimension for the same measurement previously made using three single-axis accelerometers in combination with a triaxial mounting block. The fact that the footprint is the same allows for use of all the existing tooling and test fixturing used for the 7270A.

The cost per axis of measurement for the triaxial accelerometer is roughly two-thirds that of three single-axis units on a triaxial mounting block. This makes it an ideal substitute in applications where the individual axes are not required to be repairable, such as in hard potted modules or in designs that are only used in a single penetration event.

Projected to be released by the end of the year is the Endevco® model 7284 lighted-damped, high-g shock triaxial accelerometer, which is a damped version of the 7274. It will use the same damped sensing element reported on at previous NDIA Fuze Conferences [5] [6], with a paper presented this year that will include the most up-to-date information [7]. The 7284, having light gas damping and mechanical overtravel stops, will offer more survivability in unpredictably harsh environments. However, the useful bandwidth is reduced due to the decreased resonant frequency required to achieve damping. Furthermore, the amplitude linearity range of the 7284 is 1.5 times full scale range minimum, whereas the 7274 is assumed to be linear up to the g level where it breaks because it has no damping or mechanical stops.

There are certainly trade-offs of using damped or undamped high-g shock accelerometers. However, with the realized space savings of using the triaxial accelerometer, more options are available to optimize survivability and reliability in fuze or data recorder designs. For example, one could imagine using both the 7274 and 7284 in a single design. In this installation the 7274 undamped, unstopped triaxial accelerometer will offer high bandwidth data and high linear overrange, while the 7284 damped triaxial accelerometer will provide extreme survivability in unpredictable harsh environments, preventing the loss of data if the undamped sensor is damaged.

Summary

The Endevco® model 7274 high-g shock triaxial accelerometer is a triaxial version of the model 7270A high-g shock single-axis accelerometer. The model 7274 offers a 90% reduction in envelope dimension over the existing solution for making the same triaxial measurement, which is three single-axis accelerometers on a custom-machined triaxial mounting block. It uses the same undamped sensing system as the 7270A and most of the performance characteristics are the same. Performance parameters of the 7274 were discussed and data was presented showing a transverse sensitivity of less than five percent of the axial sensitivity and a shock survivability greater than 3X the nominal range with minimal zero shift after shock. Base strain sensitivity results presented were less than 0.02% full-scale range at 250 microstrain.

Usage and handling details were discussed. Transverse sensitivity and base strain errors are minimized by using a clean, flat mounting surface. The best practice mounting method will use an adhesive between the base of the accelerometer and the mounting surface in order to enhance the strength of the mounting screws (especially in transverse loading conditions), minimize the effects of case dynamics on the data and ensure increased transmissibility of the shock input to the accelerometer. In situations where it is determined that an adhesive is not required an acoustic couplant is recommended to ensure that the accelerometer is in intimate contact with its mounting surface. The accelerometer's instruction manual should be reviewed for more details relating to usage and handling. Ideal applications for the triaxial accelerometer were discussed. The 7274 is an ideal candidate for applications that do not require the individual axes to be repairable, such as in hard potted modules or in designs that are only subjected to a single shock event. Certain applications requiring repairable axes may still require the use of three single axis accelerometers.

The Endevco® model 7284, scheduled for release by the end of 2012, is introduced as a damped version of the 7274. The damped, stopped 7284 will offer more survivability in unpredictable and harsh environments than the undamped 7274, but less bandwidth and linear overrange capability. To balance the trade-offs, it is conceivable to include both versions in a single design where the 7274 collects high bandwidth data while the 7284 ensures data collection in extreme environments where the undamped sensor might fail.

References

[1] "Practical Understanding of Key Accelerometer Specifications," Technical Paper No. 328, Meggitt (San Juan Capistrano), Inc.

[2] "Model 2911 Vibration Standard-Shaker," Datasheet No. 2911, Meggitt (San Juan Capistrano), Inc.

[3] "Model 2925 AACS Comparison Shock Calibrator (POP)", Datasheet No. 2925, Meggitt (San Juan Capistrano), Inc.

[4] "Model 7274 Triaxial Accelerometer", Instruction Manual No. IM7274 Revision A1, Meggitt (San Juan Capistrano), Inc., Revised January 2012.

[5] T. Kwa, G. Pender, J. Letterneau, K. Easler, R. Martin, "A New Generation of High-Shock Accelerometers with Extreme Survivability Performance," Proc. 53rd NDIA Fuze Conference, Lake Buena Vista, FL, May 21, 2009.

[6] R. Martin, G. Pender, J. Letterneau, T. Kwa, "Results from Preliminary Testing of a New Generation of High-Shock Accelerometers with Extreme Survivability Performance," Proc. 54th NDIA Fuze Conference, Kansas City, MO, May 13, 2010.

[7] R. Martin, J. Letterneau, "High Survivability Accelerometer for Fuze Applications," Proc. 56th NDIA Fuze Conference, Baltimore, MD, May 16, 2012.