Survivability and linearity of the high-survivability, high-shock 60,000g accelerometer
Introducing the high-survivability, high-shock 60,000g accelerometer.

Performance parameters of the Endevco® brand 20,000g high-survivability, high-shock accelerometer were presented at the 80th Shock & Vibration Symposium. This paper introduces a new 60,000g range to complement the Endevco family of high-shock accelerometers. Linearity data from Hopkinson bar testing up to 60,000g (full scale) is presented to show performance to full range; while survivability and zero shift data from Hopkinson bar testing up to 400,000g (nearly seven times full scale) is presented to show the accelerometer’s ruggedness. This new family of damped accelerometers incorporates squeeze-film damping and mechanical over-travel stops to extend the survivability. Due to the nature of squeeze-film damping, the mechanical overtravel stops appear as soft stops in the time history, resulting in a sensitivity that rolls off with increasing acceleration above full scale. An illustration of this phenomenon is offered for the engineer responsible for data acquisition and data reduction. The performance of the new 60,000g accelerometer to full range, in combination with its extreme survivability, make it an ideal candidate for high-g shock measurements, including fuzing, blast testing and pyroshock.

Introduction

The legacy Endevco undamped high-shock accelerometer has been the standard in high-g shock measurements for over 25 years. Although still very reliable in many environments, the combination of its undamped sensing system along with no mechanical over-travel stops allows the accelerometer to resonate when subjected to very high frequency contents which can result in breakage. The first solution to this problem for high frequency environments was the mechanically filtered option. Designed by Dr. Vesta Bateman while at Sandia National Laboratories, this accelerometer has been successfully used in pyroshock for many years, and its performance characteristics have been well defined in literature. The size, however, excludes its use in certain applications that demand small size, like on-board fuzing applications. Because of this, over the past few years there has been a push in the direction of light gas damping to improve the ruggedness and survivability of small-size high-shock piezoresistive accelerometers. Released to market in July 2010, the Endevco high-survivability, high-shock 20,000g accelerometer is a rugged lightly gas damped 20,000g range piezoresistive accelerometer packaged in a leadless chip carrier (LCC) package for surface mount fuzing applications. Expected to release to market in March 2011, the Endevco high-survivability, high-shock 60,000g accelerometer is Meggitt Sensing Systems’ newest addition to its family of high-survivability, high-shock damped accelerometers, boasting a 60,000g range with greater than four times overrange capability.
This paper limits the scope of the discussion of the new damped high-shock 60,000g accelerometer to linearity to full range, survivability and zero shift performance to greater than four times range. It will also include a brief discussion of squeeze film gas damping and soft mechanical stops. To date, the majority of the testing has been performed at Meggitt Sensing Systems in San Juan Capistrano, CA, primarily on a 5/8” diameter Hopkinson bar. Further characterization has been initiated at the Dynamic Shock Facility of the Air Force Research Laboratory (AFRL) at Eglin Air Force Base where a similar test series has already begun on the new damped high-shock 20,000g accelerometer. Testing performed to date at Eglin AFB consists of Hopkinson bar testing to 80,000g using both a legacy undamped accelerometer and a laser vibrometer as a reference and testing on the VHG (very high g) shock machine to 50,000g. Data from these test series are currently being analyzed and will be presented at a later date.

Test configurations
All data presented in this paper were taken on a 5/8” diameter titanium Hopkinson bar in the shock lab at Meggitt Sensing Systems in San Juan Capistrano, CA (MSS-SJC). Various acceleration levels are obtained by changing the configuration of the projectile (or striker) and the mitigator, a sacrificial material used at the end of the Hopkinson bar to shape the pulse amplitude and width. In general, the higher acceleration levels are obtained with a metal to metal impact.

The leadless chip carrier (LCC) package of the new damped high-shock accelerometer is intended for surface mount (SMT) applications, and it doesn’t lend itself to laboratory testing. For this reason, a new test fixture (shown in Figure 2) was developed to accommodate laboratory testing in high shock environments.

A traditional Hopkinson bar configuration uses strain gages mounted at the middle of the bar as the reference for the shock event. There are concerns when testing to higher acceleration levels that result in much shorter pulse widths. The main concern is that a Hopkinson bar has a certain frequency limit above which the shock pulse traveling in the bar is dispersive, meaning different frequencies are traveling at different speeds. The data can be corrected for this dispersion effect, but it would require very accurate measurement of certain material properties for each bar used. Instead, an alternate approach was used that utilized a reference accelerometer. The 5/8” diameter Hopkinson bar isn’t large enough to accommodate side-by-side testing of accelerometers, so a new reference accelerometer was developed for in-house testing in a back-to-back configuration. The reference accelerometer, shown in Figure 3, has an integral stud that mounts directly to the Hopkinson bar. The two threaded holes in the body of the reference accelerometer allow for testing of accelerometers with the traditional 4-40 bolt pattern.

Test data are presented for acceleration in both the sensitive axis and the cross, or transverse, axis. The sensitive axis configuration, shown in Figure 4(a), uses the high-shock test fixture in combination with the back-to-back reference accelerometer mounted on the Hopkinson bar.

Figure 1: Shock accelerometers (not to scale): (a) legacy undamped, (b) mechanical filter option, (c) new damped.

Figure 2: High-shock test fixture.

Figure 3: Reference accelerometer used for high g shock testing.
The cross axis configuration uses an alternative test fixture to orientate the accelerometer on the reference accelerometer so that the acceleration is directed in the transverse axis, shown in Figure 4(b).

Linearity

Based on laboratory test data the new damped high-shock accelerometer has been shown to be linear to at least 1.5 times full range (to within approximately ±5%). An illustration of this linearity is shown in Figure 5. Each data point on the plot in Figure 5 corresponds to a single Hopkinson bar shock event in the sensitive axis, where the peak acceleration was measured by the 7270AM17 reference accelerometer.

The slope of the best fit straight line (BFSL), or curve fit, of the data is the measured sensitivity of the accelerometer. In this case the BFSL is forced through zero because any zero measurand offset (ZMO) of the accelerometer was removed prior to data analysis. All of our high-shock accelerometers receive a shock of at least 3X range on the Hopkinson bar before being calibrated.

Survivability and zero shift after shock

Survivability is measured by how high a shock level an accelerometer can be subjected to without failure. Zero measurand offset (ZMO) is defined by the voltage output of an accelerometer when at rest (i.e. no acceleration). Zero shift after shock is the measure of how much the ZMO changes as a result of a particular shock event. Survivability and zero shift after shock are critical parameters for certain applications where the peak accelerations are not always known and the ZMO is used to make a critical measurement. For example, the technology employed in a void sensing fuze application measures the number of voids, which show up in the time history as very low level accelerations. The accelerometer needs to survive the high acceleration events of the buried concrete layers in a bunker, while still making accurate readings at low levels of acceleration while in the dirt and air gaps. Scatter plots
of zero shift after shock while tested in the sensitive and cross axes are shown in Figures 6 and 7 respectively.

The first take away from these plots is the acceleration levels to which the 60,000g accelerometers are tested to. In the sensitive axis a total of 12 damped high-shock accelerometers are tested without failure to acceleration levels upwards of 410,000g, or 7X the full scale range. The zero shift values at accelerations up to 90,000g, or 1.5X range, are less than 40g, with the majority of the points falling below 10g. Less sensitive to zero shift in the cross axis, the data for 3 units tested in the cross axis show zero

Figure 6: Zero shift after shock in the sensitive axis (12 units tested).

Figure 7: Zero shift after shock in the cross axis (3 units tested).
shift values of 40g or less up to 270,000g, or 4.5X range. To put things into perspective 40g is only 0.07% of 60,000g (the full scale range), and the maximum shift recorded of ~400g is only 0.7% of 60,000g.

Important to mention here is that the plots above are the result of laboratory testing on a Hopkinson bar, which can’t exactly simulate the actual shock environment. The next phase of testing on the damped high-shock accelerometer will include simulated environments, which will include cannon, sled and flight tests.

**Damping and soft mechanical stops**

Both damping and mechanical stops are key design features contributing to the high frequency, high shock survivability of the new damped high-shock accelerometer. The design employs squeeze film damping technology, which is basically the squeezing (and displacing) of air as one plate (the proof mass) moves towards a second fixed plate (the mechanical stop). Even with such a small amount of damping, on the order of five percent, the amplification factor at resonance is significantly reduced as shown in Figure 8.

The time history of Figure 8 shows a new damped high-shock accelerometer and an undamped reference accelerometer tested in a “back-to-back” configuration on a Hopkinson bar at 150,000g. Less apparent in this plot is the influence of the mechanical stops on the peak acceleration recorded by the damped unit. Another demonstration of the mechanical stops is shown in Figure 9 below.

In the figure above there are a series of four Hopkinson bar tests at increasing acceleration levels. Shown in Figure 9(a) there is a nearly full scale test with no contribution from the stops. The next three plots (Figure 9(b) thru 9(d)) show the acceleration output of the new damped high-shock accelerometer being constrained by the mechanical stops. You’ll notice that the constrained output does not remain constant as the acceleration level increases; this is an illustration of why we call them soft mechanical stops. Recalling the previous discussion of squeeze film damping, as the proof mass approaches the stop, air is being squeezed and displaced. The shock event is usually over before enough air is displaced and the proof mass can fully reach the physical stop. With soft stops you will rarely see a hard clipping of the signal as you might expect from an undamped accelerometer with stops, or an electrical clipping as a result of saturating an amplifier. Instead the soft stop shows up as a continuous reduction in sensitivity with increasing acceleration levels outside of the linear region. Plotting the peak output of the damped 60,000g accelerometer at increasing acceleration levels will further illustrate this point.

In looking at Figure 10 you can see the sensitivity begin to roll off above the linear region, marked by the pink diamonds. The horizontal lines marked “2X RANGE” and “3X RANGE” designate the output, in mV, of the accelerometer by extrapolating a linear sensitivity to 2X and 3X the full range. The soft stops are starting to engage after 100,000g and seem to settle in around 330,000g (or about 2.5X range). The scatter about the 330,000g line is due to the proof mass approaching but never fully reaching the stop.

Another interesting take-away from Figure 10 is that the 60,000g damped accelerometer is reasonably linear to 2X full range, or 120,000g, where the dashed lines above and
below the curve fit line represent a ±5% tolerance in the calculated sensitivity. A data review of many different units show this upper end of the linear region is at least 1.5X full range, or 90,000g.

**Summary & future testing**

Many prototype damped high-survivability, high-shock accelerometers have been tested up to 400,000g on a Hopkinson bar, in both the sensitive and cross axes, with no failures and minimal zero shift after shock, especially up to 90,000g. The extension of survivability can mainly be attributed to the addition of light squeeze film gas damping and soft mechanical over-travel stops. The light damping reduces the amplification factor at resonance while the mechanical stops prevent the proof mass from moving to unsafe displacement levels. The mechanical stops are referred to as soft stops, which are shown as a gradual reduction in sensitivity with increasing acceleration levels outside of the linear region, which is typically 1.5X full range. Perhaps just equally as important to survivability, but not discussed in this paper, are proprietary manufacturing processes used at Meggitt Sensing Systems’ MEMS foundry in Sunnyvale, CA (MSS-SV). Building on many years of experience in MEMS manufacturing, the team at MSS-SV has developed another quality MEMS sensor.

Future testing will subject the 60,000g damped high-shock accelerometer to simulated environments at the Dynamic Shock Facility at Eglin AFB, including cannon, sled and flight testing. Even though the 60,000g damped accelerometer is scheduled to release to market in March 2011 in the LCC package presented, the work doesn’t stop there. Understanding the current surface mount package is not ideal for laboratory type testing, we have initiated others products, matched in performance, with the traditional bolt-mount package, in both single axis and triaxial configurations.