



# Accelerometer Shock Sensitivity Calibration Using a Pneumatic Exciter



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# **Accelerometer Shock Sensitivity Calibration Using a Pneumatic Exciter**

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## **Abstract**

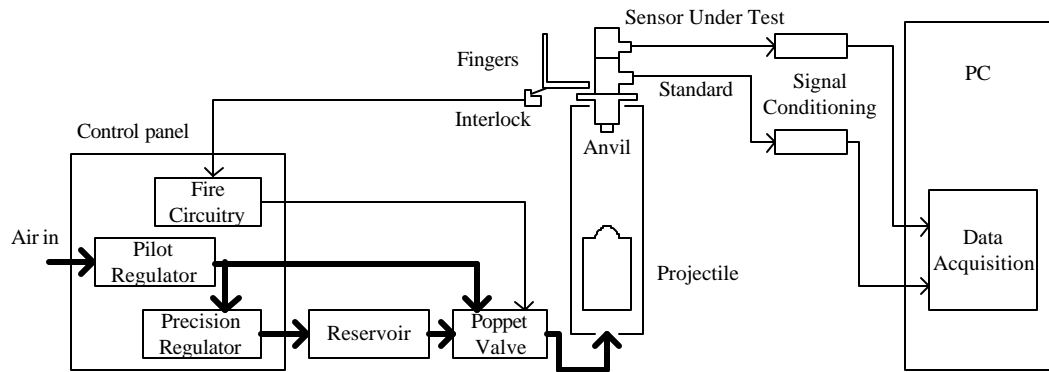
A system for the measurement of accelerometer shock sensitivity is described, complying with the requirements of comparison calibration per ISO 16063-22 “Methods for the calibration of vibration and shock transducers - Part 22: Shock calibration by comparison to a reference transducer”. This system is comprised of a newly designed exciter, a new back-to-back comparison standard with integral charge convertor, and new software. The design features are described which result in improvements over previous similar systems, including averaging of multiple shocks in linearity measurements, quieter operation, more durable components, and greater range of input levels.

## **Introduction**

Shock accelerometers measure the high-amplitude, short-duration accelerations often associated with transient events. These acceleration levels often reach or exceed the recommended full scale of transducers used for measurements. Since an accelerometer might not be perfectly linear, that is, its sensitivity might vary with the input amplitude, these accelerometers can introduce errors into shock measurements, increasing uncertainties. Calibration can reduce these uncertainties if tests are performed at levels typical of the actual measurement. However, the most commonly used calibration techniques in calibration laboratories use electrodynamic shakers. Because typical calibration-quality shakers are incapable of achieving the acceleration levels of shock, alternate means were developed for secondary (comparison) shock calibration of accelerometers. These are described in ISO 16063-22 [1]. The shock methods are applicable for amplitude range from as low as 10 G to above 10,000 G, and a pulse duration range of less than 0.1 ms to 8.0 ms. This report describes a system newly designed to facilitate shock calibration, including a new pneumatic exciter, a new comparison standard accelerometer, and algorithms that improve on similar previously-developed systems.

## **System Description**

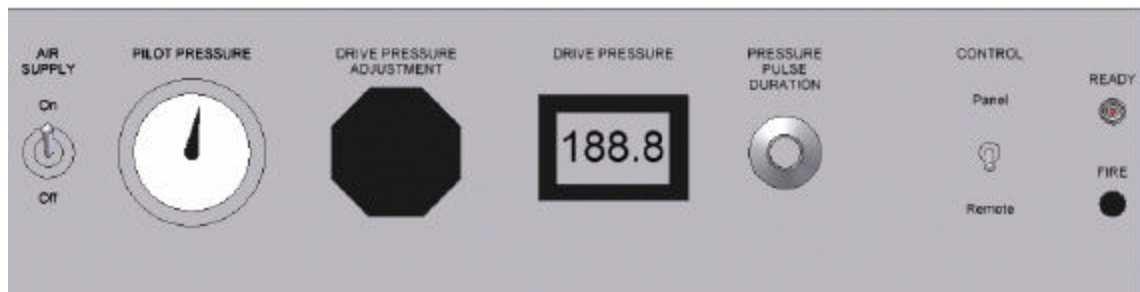
Shown schematically in Figure 1, the shock calibration system consists of an exciter using a pneumatically driven projectile, a back-to-back comparison standard, laboratory signal conditioning and PC-based data acquisition. Similar systems have been developed in this basic form; this system was designed to improve performance and be more cost effective. The exciter, standard transducer and software were custom designed for this implementation, improving in each case on the previous basic design. Signal conditioning and data acquisition were chosen off the shelf, taking advantage of the recent performance improvements in data acquisition.



**Figure 1. Schematic of the 9155C-525 Shock System by The Modal Shop.** The system includes The Modal Shop 9525C PneuShock<sup>®</sup> exciter, and the new PCB Piezotronics 301A12 Comparison Standard. Conditioners are from the 440 series conditioners from PCB, and data acquisition is from National Instruments Corporation.

### Exciter

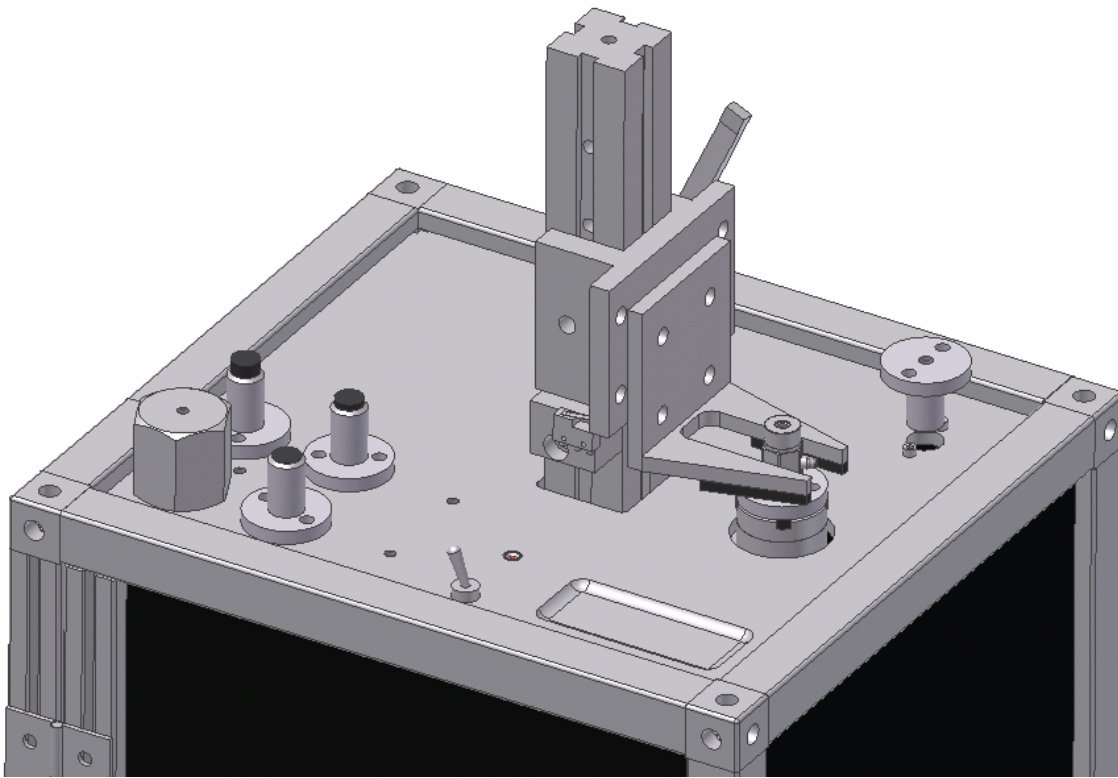
The newly designed exciter, as depicted in Figure 1, follows the basic description of a pneumatically operated piston in ISO 16063-22. The calibration is made by comparing output of the Sensor Under Test (SUT) to that of a back-to-back comparison standard. Both are mounted to an anvil chosen according to the appropriate mass and padding needed to achieve the desired shock level when struck by a pneumatically driven projectile. The PneuShock design differs from that of other pneumatic exciters, which typically house both electronics and pneumatics in one case, subjecting the electronics to damaging shocks. The separate PneuShock control panel is described in Figure 2. The exciter hardware is then shown in Figure 3.



**Figure 2. Controls and indicators of the 19" rack mountable control panel.** From left to right, the air supply toggle is provided to eliminate air consumption while the system is unused. The pilot pressure shows the first stage of regulation, controlling the air used to drive the poppet valve, which in turn quickly releases the regulated drive pressure to the projectile. The Drive Pressure Adjustment is a precision regulator, which can be a manual regulator or a potentiometer controlling an electrically controlled regulator. Drive Pressure is a 3-1/2 digit voltmeter displaying high resolution output of a piezoresistive pressure sensor. The potentiometer providing Pressure Pulse Duration controls how long the poppet valve is open, adding an extra degree of control to improve shock repeatability. The toggle switch for Control allows electronics to be switched from the front panel to a Remote source. The Ready LED is lit if the safety interlock is in the safe position. Finally, the FIRE button allows manual release of the pressure to the projectile creating the shock event.

Summarizing other differences from previously developed pneumatic exciters:

- 1) the poppet valve is vibration isolated from the structure (this is to avoid prematurely triggering the data acquisition because of the opening of the valve in the case of low level tests)
- 2) the operator has control not only of the applied pressure, but the time that the pressure is applied, for fine tuning better control at low levels and increased repeatability
- 3) the projectile is better tuned to the typical mass of the anvil transducer combination, so at impact there is more complete momentum transfer and quieter operation (measurements showed typical improvement of 8dB at 5000 G operation from 1 meter away),
- 4) the longer barrel and larger reservoir allows increased momentum, and therefore higher shock range with longer durations,
- 5) the side panels can swing fully out of the way to access all internal parts, and are on lift-off hinges for ease of maintenance (such as removing debris from worn padding from inside the barrel),
- 6) the case is floor mounted, to accommodate a longer barrel and desk-height operation.



**Figure 3. Features of the exciter.** This depiction shows the assortment of anvils with different padding thicknesses available to adjust the acceleration and pulse duration resulting from the impact. The anvil in the right corner is depicted hovering over a spanner fixture, which when engaged, allows the operator to apply torque to assemble and disassemble the anvil/standard/SUT stack. The hexagonal stock at the left can be included in the assembly as supplemental mass for the lowest range of accelerations. The assembly is inserted into the guide at the end of the barrel, which is seen poking through the plate. A fixture with padded fingers slides vertically over the anvil, to catch the assembly after its upward flight. An interlock safety switch disables the system if the fixture is not in position. For safety while manipulating the transducers, the operator can also disable the firing mechanism with the toggle switch.

## Mechanical Operation

The operator sets the applied pressure and the duration for which the pressure is to be applied. After the data acquisition is armed to capture the waveforms, the command is given to fire the pilot-operated poppet valve to release the pressure, either manually or by remote electronic control. After the shock, the transducer/anvil assembly is decelerated by the shock absorbing padding on the fingers and settles back into position, the projectile falls by gravity to the bottom of the barrel, ready for another flight. PneuShock can be fired (and data taken and analyzed) repeatedly in quick succession, every few seconds.

Although the controls of PneuShock allow careful control of the momentum of the projectile, the resultant acceleration is not a simple function of momentum. From the definition of impulse, the momentum transferred to the transducers is equal to the integral of force over the time of the impact, and it is the details of this interaction that define the shock. The thickness and stiffness of the padding determines the duration of the impact, and therefore the force that results. Simply put, for a given amount of momentum change, a short pulse from a stiff interaction results in a large force, or inversely if impact is spread over a longer time, as softer padding is deflected, the force is smaller.

Then there is another variable that determines acceleration from this force. The acceleration that occurs is equal to that force divided by the combined mass of the anvil and transducers. Two types of anvils are supplied, one made of steel and the other aluminum. The heavier steel anvil will result in a lower acceleration than a lighter aluminum anvil. By adding a supplemental mass to the anvil assembly, acceleration can be reduced further. As a guideline, Table I below suggests what range of accelerations can be achieved with which combination of pressure, pressure duration, projectile material, anvil material, padding, and supplemental mass.

**Table I. Guidelines for choosing anvils and padding**

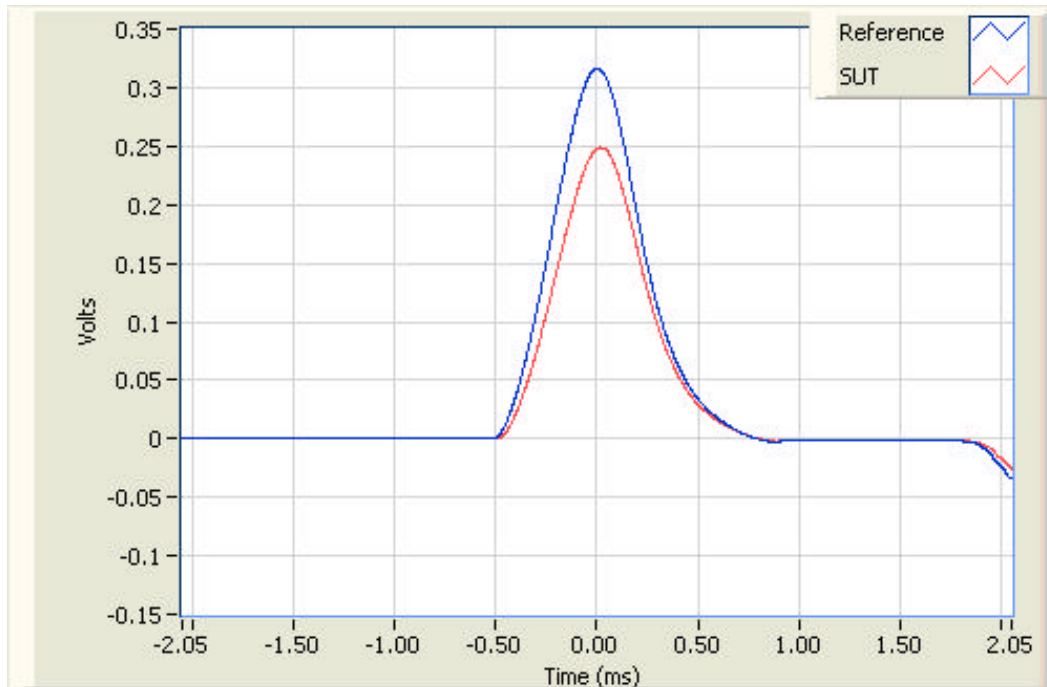
Shock Level (G)	Pulse Dur. (ms)	Anvil Mat'l	Padding	Drive Pressure (psi)	Notes
20-50	3	Steel	1/4" + felt	15-25	Supplemental mass
50-300	1.5	Steel	1/4" + felt	20-30	
100-500	1	Steel	1/8" + felt	20-35	
200-1.5k	0.5	Steel	1/16" + felt	20-35	
500-2k	0.5	Alum.	1/16" + felt	20-40	
1k-10k	0.1	Alum.	0.01" Lexan + felt	20-40	

Although the dynamics of the impact are complicated, so that it might be difficult to predict resultant shock levels from first principles, the standard accelerometer and system software provide immediate feedback. The operator quickly can predict the general configuration needed to get close, then with control panel adjustments obtains the precise shock level. It is generally more difficult, however, to obtain the desired pulse duration, and often impractical to get particular values of both amplitude and duration simultaneously.

An important consideration is that duration is closely related to frequency content. The pulse duration must be long compared to the period of resonance of either transducer, so that the responses are in the lower more-linear region of their frequency response curves. A general guideline is that the duration be a factor of 5 larger than the resonance period, so for example a transducer with a 20kHz resonance would have natural period of 0.05 millisecond, and the shortest suggested pulse duration would be on the order of 0.25 millisecond. This guideline also helps assure that the anvil assembly has approximately rigid body motion.

The shape of the curve is as important as the duration. Comparison shock calibration has the least uncertainty if the waveforms of the standard and SUT are equivalent in shape with no discernable higher-order frequency components, and that the shape is approximately a half-sine yet with no abrupt changes of

slope. (A true half sine has an abrupt leading edge, which like any event with sudden change, includes large high frequency content. This is avoided by the addition of felt to soften the initial contact.) Other sources of distortion and high frequency problems are loose mechanical connections of transducers and cables. The best practices use the manufacturer's suggested torque.



**Figure 4. Waveforms.** The basis of the calibration is the comparison of two waveforms formed by the rigid body motion from impact. Note that after the shock the two sensors are in free fall, with approximately zero acceleration after the event. Analysis of the flat regions before and after provides a measure of zero shift of the SUT. Note that 2 milliseconds after the peak a deceleration begins. This is caused by the anvils striking the padding of the fixture. The time duration between the positive and negative accelerations is adjusted by the spacing of the fingers above the anvils, defining the distance of free fall.

Distortion can also come from torn rubber padding, or if part of its adhesive has failed. The slap of loose rubber can cause discontinuities. It is good practice to inspect all mechanical connections and the integrity of the padding before any series of tests.

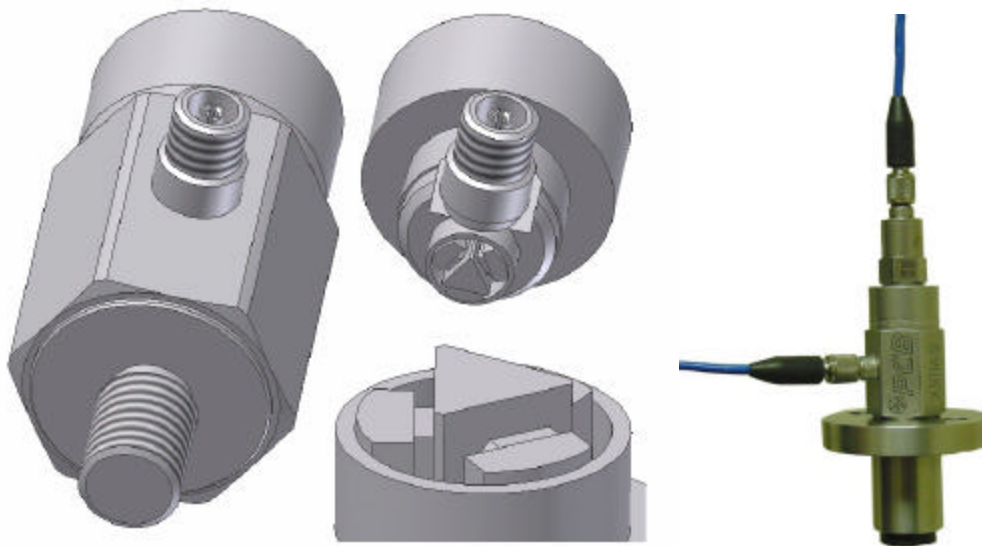
Even if padding is intact, when drive pressures are too great, the anvil padding may be overly compressed and cause poor waveforms. This can become apparent during an amplitude linearity sequence, as the pressures and shock amplitudes increase using a particular anvil. The central peak becomes a very small portion of the overall pulse duration, and the lead-in to the pulse becomes disproportionately long. (In highly specialized shock calibration terminology, the wave shape becomes “pointy”.)

The pulse shown in Figure 4 is nearly at this state, being almost more triangular than sinusoidal. The explanation for the “pointy” shape is that the pulse narrows and forces peak as the padding becomes thin compared to its original thickness. Forces and displacements are high and the relationship between force and displacement in the padding becomes nonlinear. Besides being potentially damaging to the padding, high frequencies are generated which may not satisfy the requirements of frequency content. As an amplitude linearity sequence progresses, when the pointy shape is seen, the operator should consider that it is time to change to an anvil with thinner padding. The overall duration of the pulse will decrease, but the shape will improve.

If the distortion becomes more severe during multiple shocks at the same pressure, the operator should stop the test and check the setup. It would be important to confirm the torque on threads of transducers and cables, as well as the integrity of the padding. A rupture of padding would allow metal-to-metal impact between the projectile and the anvil, which can cause transducer-damaging acceleration levels. Although the software is written so the algorithms recognize improper conditions (signal saturation, distortion, etc.), operators are advised that every waveform captured should be visually inspected for abnormalities, and if one is seen, the root cause should be determined and appropriate corrective action should be taken.

### Comparison Standard Accelerometer

A new back-to-back comparison standard was designed for this shock application. Although the basic shape is comparable to an industry-standard comparison standard transducer (which has a compression mode ceramic sensor), the principal improvement is in the new sensor subassembly. Shown in Figure 5, its quartz shear mode configuration provides long-term stability and isolation from case strains and thermal transients. Resonance frequency of the subassembly is nearly 100 kHz, giving essentially flat response to 10kHz. Integral charge conversion using ICP<sup>®</sup> circuitry significantly reduces the sources of cable-induced noise, relative to the conventional charge mode transducers. Sensitivity was scaled to approximately 0.5 mV/G, to assure linear electrical conversion to well above 10 000G. Finally, the hermetic weld on the hardened 17-4 stainless steel package gives true environmental immunity, whereas the older transducer design used an epoxy seal.



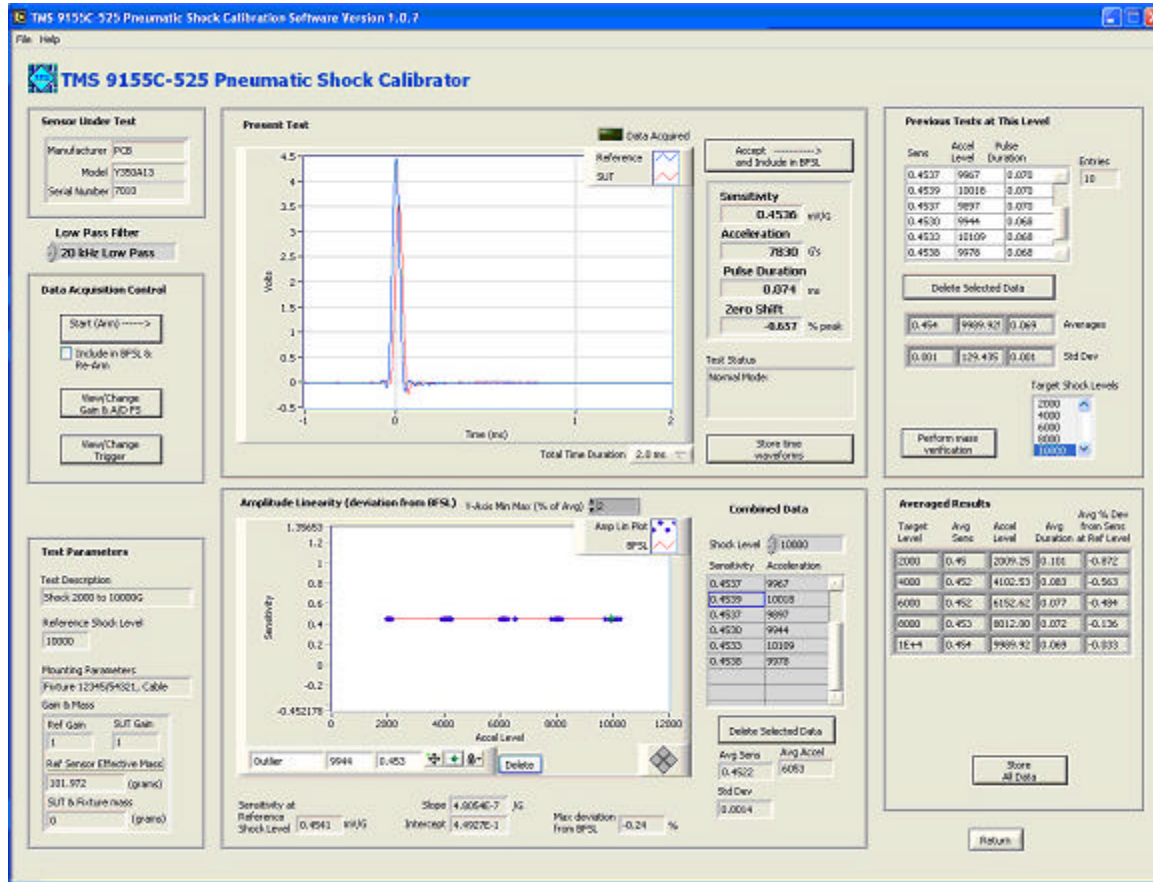
**Figure 5. PCB Piezotronics Model 301A12 comparison standard.** On the left are depictions of the standard accelerometer, showing first the integral mounting stud, then, at top center, (at the same angle but with the case removed), the internal sensor subassembly. At lower center is a close up of the quartz shear elements squeezed between the triangular center post and the mass elements held by a ring. On the right is a photograph of the standard mounted on an anvil, with a test transducer mounted in the 1/4-28 tapped hole on the top surface. For size comparison, the length of the Standard (not including the integral stud) is about 1.15" (29 mm).

As is usual, the sensitivity and frequency response is determined at low amplitude with the low uncertainty of absolute (laser interferometric) techniques. What is unusual is that the amplitude linearity of each 301A12 is established with a Hopkinson bar technique [2], verifying linearity (typically within 1%) to above 10 000G. The sensitivity also typically changes with a linear relationship to the acceleration level, as is shown on its calibration certificate.

To model the performance of the standard in the new system, the software combines sensitivity and linearity, using the sensitivity determined by the absolute vibration, and extrapolating that sensitivity to



higher acceleration levels using the slope determined in the Hopkinson bar technique. Although the Hopkinson bar sensitivity results have combined expanded uncertainty of more than 5%, the uncertainty of the slope is known to be significantly smaller than the absolute value. The system software uses this model of performance to establish the shock level measured by the standard, with a combined ( $k=2$ , 95%) expanded uncertainty no larger than 2%.



**Figure 6. Graphical interface of the TMS9155C-525 Shock Calibration Software.** The screen allows control of the digital storage oscilloscope and display of the data. Time domain data can be displayed either raw or as digitally filtered. Tables are made of the results of the algorithms which find sensitivity, peak shock level and pulse duration. At each desired shock level, the table at the upper right finds averages and standard deviation of the set. Such a table is stored for each desired shock level, and the statistical results of each set are tabulated in the lower right. The upper graph is a time-domain plot, the duration of which is operator controlled (so the operator can have the algorithms applied to a selected portion of the data set). The lower graph shows all stored results, plotting sensitivity as a function of peak acceleration level, with a Best Fit Straight Line and the calculated sensitivity at a reference level. A delete button allows removal of the worst outlier, after which the BFSL is recalculated. At the end of testing, data is stored when returning to the main software, and test reports can be created using templates in Microsoft® Excel.

### System Software

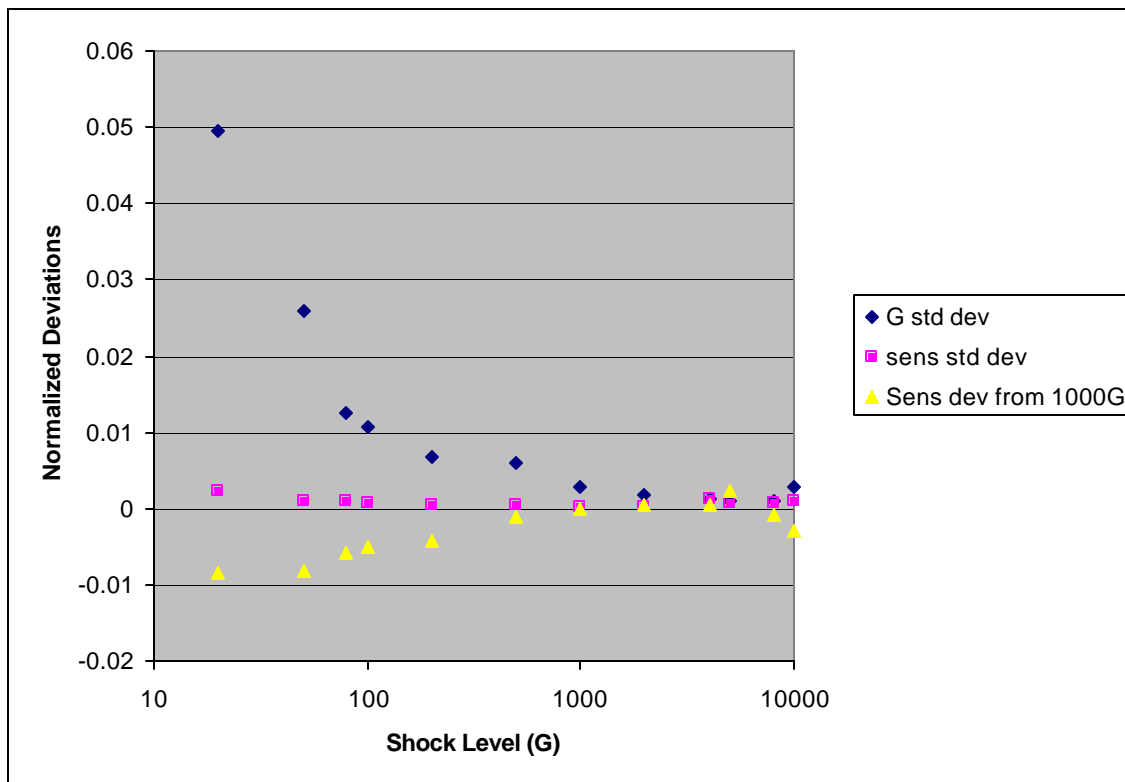
The screen of Figure 6 appears after the user selects the SUT type and desired test from the main TMS 9155C Accelerometer Calibration software. (Other tests supported by the software, not described here, might include frequency response testing on an air-bearing electrodynamic shaker.) The parameters for the sensor and the desired test are retrieved from a database, and the system gain and data acquisition parameters are configured automatically for the series of shock tests. Usually several target test levels are



listed, to determine the SUT amplitude linearity. As each level is chosen, gains are set according to the expected outputs of the standard and SUT.

The software can work with a number of off-the-shelf data acquisition cards, including new products with 24-bit resolution (118 dB dynamic range), simultaneously sampled at 204.8 kS/s. The oversampling techniques provide digital antialiasing filtering. However, it was noted that high frequency noise, particularly at high shock levels, is detrimental to the curve-fit process described in ISO 16063-22, resulting in erroneous calibration result. Thus a digital low pass filter is used on the numerical data, chosen from a selection of cut-off frequencies of 10 kHz, 20kHz, and 30 kHz. (An FFT based approach, also described in ISO 16063-22 and less susceptible to noise, is under development.)

### Results



**Figure 7. Standard deviations of shock levels and the calculated sensitivity.** The data points at each shock level represent a set of fifteen shock tests at that level with a particular combination of drive pressure, anvil and padding. The normalized standard deviation of the resultant shock level has the highest values, representing the scatter due probably to frictional forces on the projectile. Scatter in the levels below 100G is about 1 G, proportionately largest at the lowest acceleration levels, representing approximately 5% of the peak value at 20 G. The effect on the calibration is small. The standard deviation of the comparison calibration performed at these levels generally stays below 0.1%, with the worst case at 20 G of 0.25% for the particular SUT.

### Conclusions

Shock calibration of accelerometers is facilitated with a new system. New designs in the exciter, standard and software have resulted in improvements in ease of use, control, capabilities and in the gathering of statistical data.

### **Acknowledgments**

The authors wish to thank Mike Insalaco of PCB for his help with the reference accelerometer, Mark Tylman of PCB and Kevin Sill and for their work on the PneuShock software and hardware, respectively, and Dave Bailey and Kevin Rodgers of The Modal Shop for data on PneuShock performance.

### **References**

[1] ISO 16063-22 Methods for the calibration of vibration and shock transducers — Part 22: Shock calibration by comparison to a reference transducer.

[2] Dosch, Jeffrey, Lin Jing, “Hopkinson Bar Acceptance Testing for Shock Accelerometers”, Sound and Vibration, February 1999.

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