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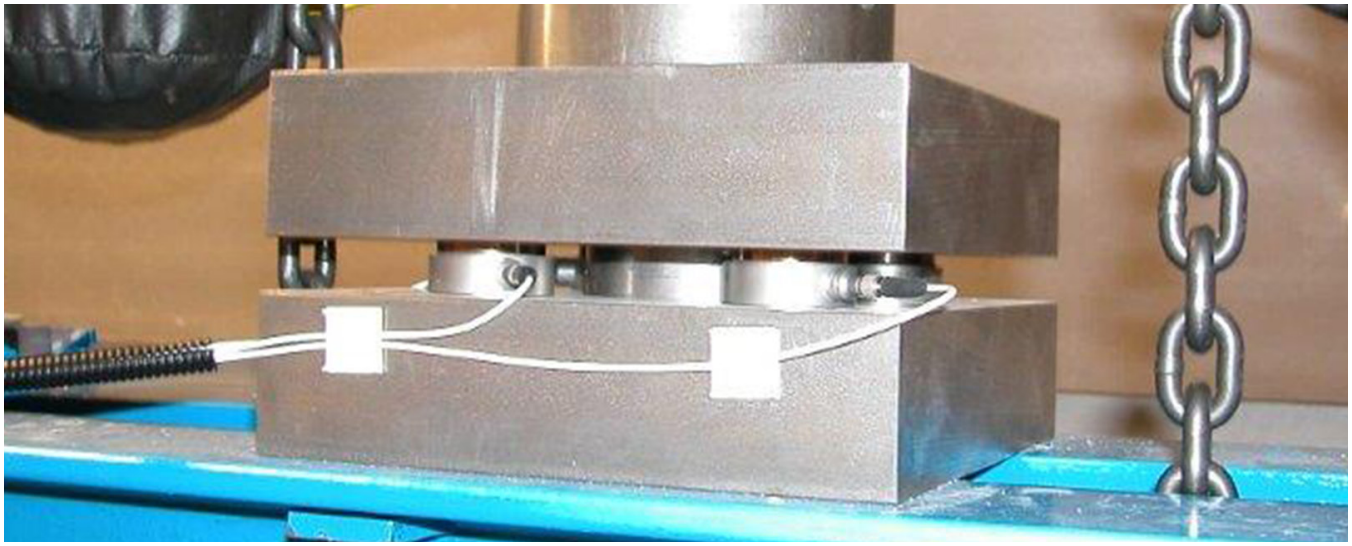

Impact and Drop Testing

With ICP® Force Sensors

Abstract

Test engineers are often tasked with providing impact energy data on various components. Design engineers request data in energy units such as Joules, yet the data must be recorded using force, velocity, acceleration, distance, and time units. The purpose of this paper is to present the test engineer with a guide for using force measurements obtained during impact testing to compute the associated impact energy.

A method for force sensor measuring range selection will be presented, allowing the test engineer to quickly assemble the required test system. Advances in quartz piezoelectric ICP® force sensor technology will be discussed to show their benefit in impact testing.

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1. Reasons for Impact Testing

Impact testing is performed to determine the energy absorbed or the energy required to fracture a unit under test (UUT). Take for example a straight-line collision, such as a car crash. Using the work-energy principle where average impact force times the distance traveled equals the change in kinetic energy, design engineers can help reduce the impact force of a car by extending the stopping distance through the use of 'crumple zones.'

Under controlled laboratory conditions, impact testing may be used to validate designs on prototype or OEM components to ensure they meet product durability and safety requirements. Several safety critical components, such as automotive bumpers, protective sports equipment, and headform testing for hardhats or helmets must meet various SAE, MIL, ANSI or ASTM test specifications in order to be produced and sold to consumers.

Destructive impact testing may also be performed and recorded to document the strength or durability of non-safety critical items for industrial use.

2. Energy and Impact Force

Design engineers usually desire to know Kinetic Energy during impact testing; an essential component to validate design criteria. The test engineer is therefore challenged to obtain the energy values using physical test methods, and then using the data to calculate the results. A simple test method of measuring impact force versus displacement, and then integrating for the area under force-displacement curve provides an output in energy units. However, what force output could the engineer expect to measure during this actual test?

The expected measuring range for the force sensor may be estimated by calculation. It is based on the work-energy principle, where average impact force times the distance traveled, equals the change in kinetic energy. It is indeed a specific application of the law of conservation of energy, which states that the potential energy, PE, before an event must equal the kinetic energy, KE, after an event. [1]

$$PE = KE$$

For a simple drop test, where m = mass, h = drop height, g = acceleration of gravity, and v = velocity at impact, the conservation of energy equation is:

$$mgh = \tfrac{1}{2}\, mv^2$$

The impact velocity is independent of mass. Solving from the conservation of energy equation above and neglecting drag forces caused by air resistance, velocity is calculated from:

$$v = \sqrt{2gh} \qquad \textbf{Equation 1}$$

2a. Relationship Between Force and Distance

Using the work-energy principle, the next step for the test engineer is to estimate the expected force. The net work done during an impact is equal to the average force of impact multiplied by the distance traveled during impact.

$$W_{net} = \tfrac{1}{2} m v_{final}^2 - \tfrac{1}{2} m v_{initial}^2$$

In a drop test application, $W_{net} = \tfrac{1}{2} m v_{final}^2$ since the initial velocity ($v_{initial}$) is equal to zero.

Assuming one could easily estimate the impact distance, the average impact force, F, is calculated as follows:

$$F = \frac{W_{net}}{d} \qquad \text{where d = distance traveled}$$

The test engineer must therefore estimate the distance traveled after impact in order to select an impact force sensor with the proper measuring range. Distance estimation is not a simple task for the test engineer because most structures are rather complicated.

Whether or not there is a perfectly elastic collision can affect the distance estimation and thus the resulting force calculation. For the purpose of this paper, a perfectly elastic collision means a perfect rebound after impact. To explain this, suppose a steel ball bearing is dropped from a certain height onto a foam pad. Since it penetrates the material, the material is absorbing the energy and thus the impact force is minimized and is therefore not a perfectly elastic collision. On the other hand, if the same steel ball is dropped on to a steel plate, it may rebound back to the same height to which is was originally dropped. Thus, very little energy is absorbed. The impact force is very large and a near perfect elastic collision has taken place.

Table 1 compares various penetration depths versus the resulting impact force from a 10 lb (4.5 kg) object dropped from a height of 39.4 in (1m).

Table 1
Work Energy Method of Obtaining Force Estimate

Work Energy Method using Estimated Displacements							
Material	**h (m)**	**m (kg)**	**v_{final} (m/s)**	**KE (J)**	**d (m)**	**F (lbs)**	**F (N)**
Steel	1	4.5	4.427	44.1	0.0001	99,137	441,000
Plastic	1	4.5	4.427	44.1	0.1	99	441
Foam	1	4.5	4.427	44.1	5	2	9

2b. Relationship Between Force and Time

Another approach to determine the expected impact force is to estimate the pulse width of the expected force-time curve. We can use the pulse width and employ Newton's 2nd law of motion, F=ma to calculate the expected impact force.

Using the final velocity calculated from the conversation of energy Equation 1, $v = \sqrt{2gh}$, we may compute the resulting impact acceleration. This acceleration term is dependent on the pulse width of the force-time curve and must therefore take on an estimated value based on various material types, similar to the way impact distance was estimated.

Impact acceleration may be calculated from the change in velocity during the pulse width time, or

$$a = \frac{dv}{dt} = \frac{dv}{t_{pulse}}$$

The highest peak impact forces occur when there is a steel-on-steel impact. If we assume a perfect rebound, which approximates steel on steel impacts, the initial and final velocities are equal in magnitude, but opposite in direction and thus are additive. The resulting peak acceleration may be calculated from:

$$a = \frac{v_{initial} - v_{final}}{t_{pulse}} = 2 * \frac{\sqrt{2gh}}{t_{pulse}} \qquad \textbf{Equation 2}$$

It is important not to confuse the acceleration due to free fall gravity (g) used in the impact velocity calculation (Equation 1) with the impact acceleration (Equation 2). The impact force is then calculated from Newton's 2nd law equation:

$$F = ma \qquad \textbf{Equation 3}$$

Pulse width, and thus acceleration, varies just like the penetration distance as outlined in the work-energy principle. The softer the impact surface, the smaller the resulting impact force as the soft surface slows down the impact, spreading out the pulse width over a longer period of time. To compare the resulting impact force calculation method of Newton's 2nd law of motion, three test materials have been tabulated in Table 2.

Table 2
Pulse Width Method of Obtaining Force Estimate

Newton's 2nd Law Method using Estimated Pulse Widths							
Material	**h (m)**	**m (kg)**	**v_{final} (m/s)**	**KE (J)**	**t_{pulse}**	**F (lbs)**	**F (N)**
Steel	1	4.5	4.427	44.1	0.0005	18,068	80,294
Plastic	1	4.5	4.427	44.1	0.002	4,517	20,076
Foam	1	4.5	4.427	44.1	0.100	90	400

3. Drop Test Example

Instron is a well-known leader in advanced material and component testing techniques. They supply instrumentation, support services and expertise for testing materials, products and structures. [2] Test engineers needed to develop an impact test machine for automotive bumper testing. The bumper was required to absorb approximately 3,000 Joules in a designated crumple zone.

Instron engineers modified their model 8150-drop tower shown in Figure 1. It is capable of generating 27.8 kJ of energy from a drop height of 96 in (2.4 m) and mass of 1,000 lb (454 kg). The drop tower was selected for its large dimensions, which were required to accommodate the bumper.

The impact crosshead is supported by four PCB Piezotronics model 203B ICP® quartz force rings, each having a 20 klb (90 kN) compression rating for a total impact range of 80 klb (355.9 kN). Figure 2 shows a close up of the crosshead. The output of each sensor is routed to the BNC input jack on a PCB model 484B06, ICP® sensor signal conditioner. All signal conditioner output channels, which initially provide independent DC signals, are then routed to a data acquisition card where Instron's Dynatup® Impulse data acquisition and analysis system sums and then displays the output as a time waveform.

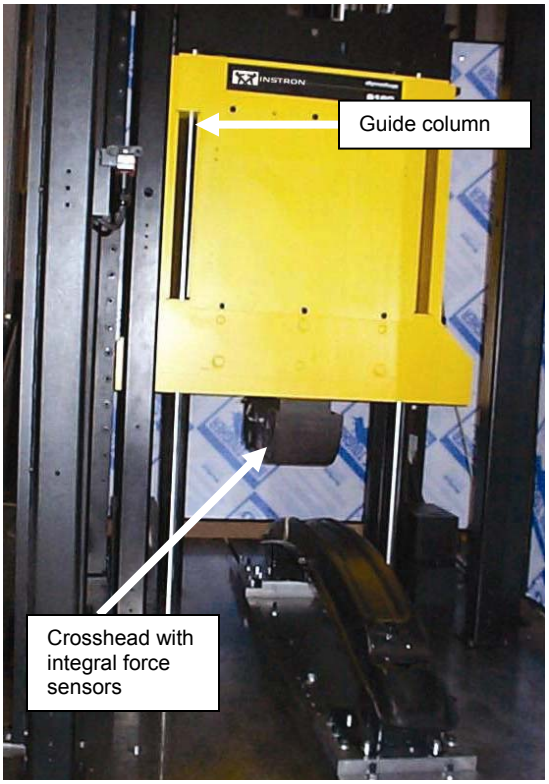


Figure 1
8150 Drop Tower
Courtesy of Instron

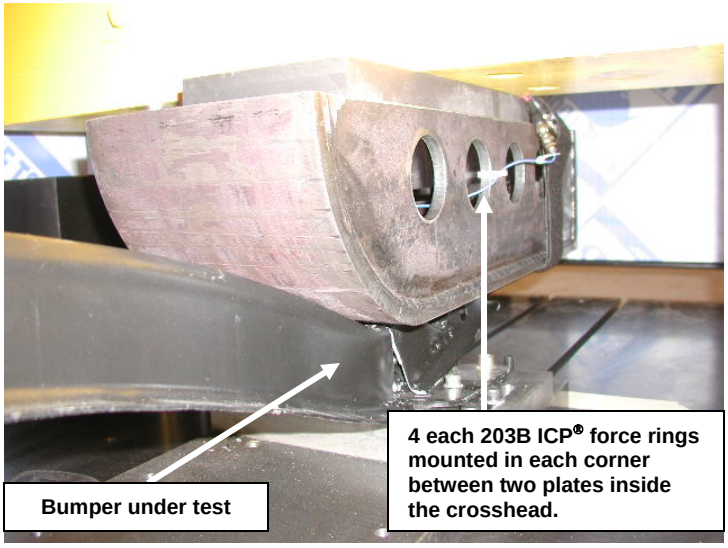


Figure 2
Sensor Mounting Between 2 Plates
Courtesy of Instron

Before selecting the model 203B ICP® force ring, Instron applied the principles in this paper. Even though the crumple zone is designed to absorb energy through displacement of the metal, and thus would not produce a steel-on-steel perfect rebound, the engineers used the perfect rebound assumption to ensure they had plenty of force sensor capacity for future over testing of the bumper to failure. One sample drop mass of 793.8 lb (360 kg) was dropped from 35.4 in (0.9 m) with an estimated crumple zone pulse width of 10 msec. Via Newton's second law force estimation method, this would result in 68,000 lb (302.5 kN).

Eqn. 1

$$v = \sqrt{2gh} = \sqrt{2 * 385.92 \text{ in/sec}^2 * 35.4 \text{ in}} = \sqrt{27{,}323.1 \text{ in}^2/\text{sec}^2} = 165.3 \text{ in/sec}$$

Energy

$$KE = \tfrac{1}{2}mV^2 = \tfrac{1}{2} * \frac{793.8 \text{ lb}}{385.92} * (165.3 \text{ in/sec})^2 = 28{,}101.5 \text{ lb - in}$$

$$= 3175.2 \text{ N-m} = 3175.2 \text{ J}$$

Eqn. 2

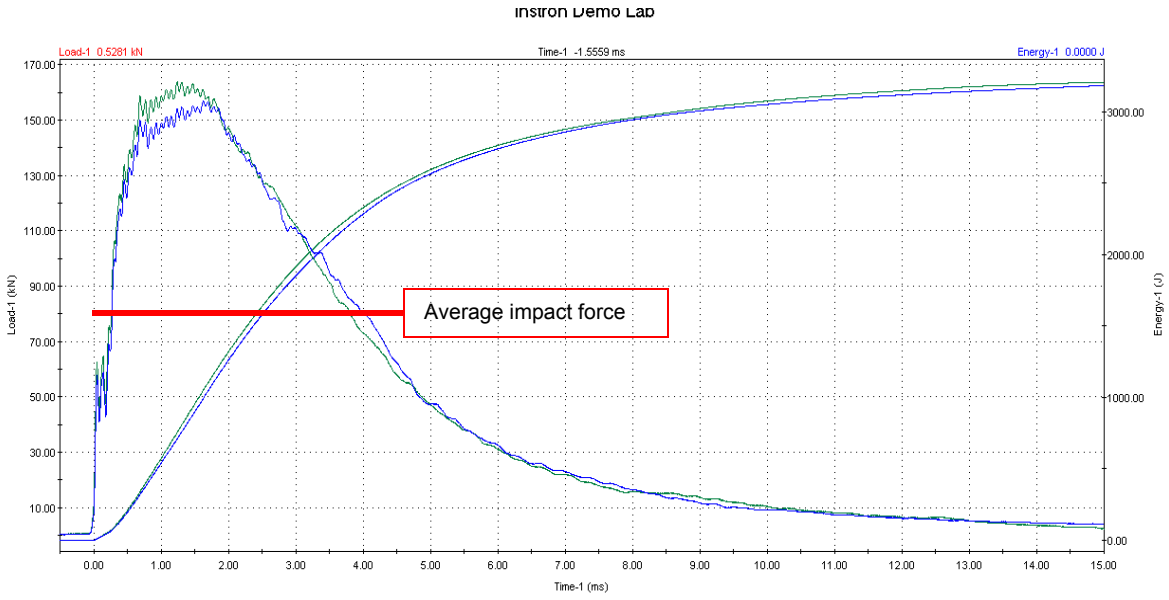
$$a = \frac{2 * \sqrt{2gh}}{t_{pulse}} = \frac{2 * 165.3 \text{ in/sec}}{0.010 \text{ sec}} = 33{,}060 \text{ in/sec}^2 \quad [85.7 \text{ g peak}]$$

Eqn. 3

$$F = ma = \frac{W}{g} * a = \frac{793.8 \text{ lb}}{385.92 \text{ in/sec}^2} * 33{,}060 \text{ in/sec}^2 = 68{,}000 \text{ lb}$$

Actual drop test data, shown in Chart 1, resulted in Kinetic Energy of 3,196 J, peak force of 36,035 lb (160.3 kN), and a pulse width of 15.17 msec. Running this actual pulse width through our math model for Newton's second law, we obtain an expected force of 44,826 lb (199.4 kN). This shows that perfect rebound assumption is adequate to ensure we select a suitable force sensor capacity.

Chart 1
Force & Energy vs. Time for Bumper



To cross check our math, we may use the work-energy principle derived in Section 2a. The displacement of the bumper after impact was approximately 1.5 in (0.038 m). If we estimate the average force from the curve in Chart 1 to be 19,108 lbs (85 kN), then the energy is calculated as follows:

$$W_{net} = F * d = 19{,}108 \text{ lb} * 1.5 \text{ in} = 28{,}662 \text{ in-lb} = 3{,}238 \text{ N-m} = 3{,}238 \text{ J}$$

This outcome is reasonable since both the measured data and Newtonian calculation produced results of a similar magnitude.

4. Selecting a Force Sensor

As previously shown, harder test materials have a higher impact force and smaller pulse width. The test engineer must select a force sensor that is several times stiffer than the UUT. If not, the sensor will absorb some of the impact, resulting in measurement inaccuracies.

Although strain gage technology is commonly taught and widely used, quartz piezoelectric ICP® force sensors provide technical advantages for impact applications. ICP® force sensors have stiffness a few orders of magnitude higher than strain gage load cells. They can easily measure to several tens of kilohertz. This is well beyond the ringing frequency of most strain gage load cells. Additional benefits of high stiffness ICP® force sensor technology include; small size, low mass, and overload protection. [3]

Sensitivity of a strain gage load cell is fixed by the stiffness of the deflecting structure, which must be sized for the desired measurement range. Foil strain gages are bonded to the flexure and a change in electrical resistance occurs as they deflect, or strain, under load. Most strain gage load cells require a deflection of 0.001 to 0.003 inches (0.025 to 0.076 mm) in order to reach full-scale output. This equates to a stiffness of only 0.03 to 6.7 lbs/μin (0.005 to 1.173 kN/ μm) for a 100 lb and 10k lb (450 N and 45 kN) full-scale range respectively.

Quartz piezoelectric ICP® force sensors produce a charge output as a result of miniscule stresses on a crystal lattice as opposed to deflection associated with a bonded foil strain gage. This charge is converted directly to a voltage output using the internal ICP® circuit. The high frequency response of ICP® force sensors is determined by the mechanical characteristics of mass and stiffness.

The natural frequency of a sensor may be calculated from the following equation:

f_n in kHz = ½π* √ k/m, where k = stiffness in N/m and m = mass in kg[4]

ICP® force sensors achieve higher frequencies since frequency is proportional to the square root of stiffness and inversely proportion to the square root of the mass.

The rise time of a force sensor must be faster than the expected impact pulse width in order to measure properly. Rise time is defined as the time it takes a force sensor to rise from 10% to 90% of its final value when subjected to a step input. It is complicated to compute the rise time for force sensor applications because mounted natural frequency depends on the particular application. The more mass on top of the sensor the lower the natural frequency. The lower the natural frequency, the slower the rise time. ICP® force sensor rise time may be estimated as one half of the natural period of the sensor:

Tp = ½*(1/fn), where, fn = natural frequency and Tp = time to peak.

For the model 203B ICP® force ring used in the drop test example, the un-mounted natural frequency is 60 kHz and the rise time is approximately 8.3 μsec.

Another benefit of ICP® sensors is a 5-volt raw output at full scale, whereas the full-scale raw output of a strain gage load cell may only be up to 20 mV (using a 2 mV/V strain gage with 10 Volt DC power supply). From the drop test example, the model 203B ICP® force ring has a broadband resolution of 0.40 lb-rms (1.8 N-rms), or 0.1 mV. The high voltage output of the ICP® sensor therefore provides a significant benefit in terms of signal to noise ratio, especially when the test is remote and requires a long cable run.

5. ICP® Force Sensor Configurations

Five ICP® force sensor configurations are commonly available and include general purpose, ring, impact, penetration, and 3-axis styles. A representative picture of each may be found in Figure 3 and a table summarizing key specifications in Table 3.

Figure 3
ICP® Force Sensor Configurations

208C05 205C 200C50 208A22 260A11

Table 3
ICP® Force Sensors Specifications

Model	Range lbs (kN)	Sensitivity mV/lb (mV/N)	Stiffness lbs/ µ inch (N/ µ m)	fn (k Hz) unmounted
208C05	5,000 (22)	1 (0.22)	6 (1.05)	36
203B	20,000 (90)	0.25 (0.06)	23 (4)	60
200C50	50,000 (220)	0.1 (0.022)	97 (17)	30
208A22	100 (450)	50 (11)	5 (0.88)	18
260A11				
Fz	1,000 (4.5)	2.5 (0.56)	10 (1.75)	90
Fx,y	500 (2.2)	10 (2.2)	4 (0.70)	

ICP® impact force sensors are typically supplied with specially designed impact caps. The convex surface transmits impact loads evenly across the sensor, providing better measurement results and preventing sensor damage. Caps also compensate for misalignment of the UUT or drop mass. They also provide a wear surface and may be replaced in the event the surface becomes damaged. These impact sensors, such as the PCB ICP® models 208C05, 200C50 and 208A22, may be directly exposed to the UUT or impact cross head.

In some cases, such as the Instron automotive bumper example, a larger force range and impact surface is required. Thus, multiple force ring style ICP® sensors, such as PCB model 203B, may be used in series between an impact plate and base plate as shown in Figure 4. It is the intent of this design that each sensor within the structure absorbs 25% of the impact force. Voltage signals may be monitored individually or summed.

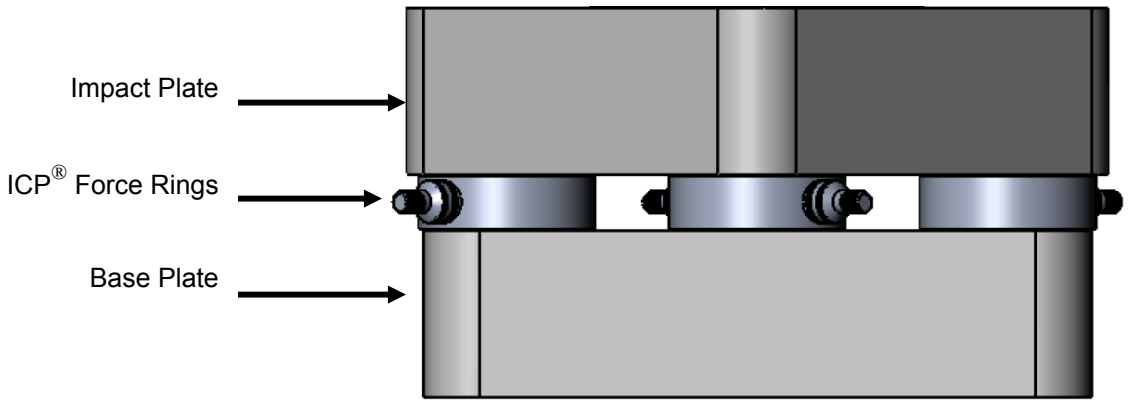


Figure 4
Side View of Force Plate Assembly

Another interesting sensor for single impact events, when it is desired to monitor the impact force simultaneously in 3 orthogonal directions, is the PCB ICP® 260 series, 3-component force ring (see Figure 3). As with the single channel models, each x-y-z axis provides an independent output signal proportional to the force input. Special models may also be purchased that provide six degrees of freedom, giving moment output around each axis (Mx, My, Mz) in addition to the standard x-y-z axis force signals.

6. Conclusions

Making impact force measurements is a proven way to document that the test engineer obtained the proper energy during an impact test. By assuming a perfect rebound for steel or estimating the pulse width for other materials, the test engineer may use Newton's 2nd law to approximate the required force sensor capacity. Test data shows that Newton's math model can indeed be used to select the proper capacity.

Attributed to their high stiffness, quartz piezoelectric ICP® force sensors have the stiffness required to measure high impact forces with fast rise times and the durability required to perform and survive in harsh test conditions. Various standard configurations have been developed exclusively for impact applications that allow the test engineer to perform testing with great ease.

7. Bibliography

1. “Hyper Physics, Mechanics,” Nave, R., National Science Teachers Association, 2001

2. “Impact Testing Solutions,” WB1238, Instron Corporation, 2006

3. “Automotive Component Durability Testing using Quartz Piezoelectric Force Sensors,” Metz, R., Automotive Testing Expo, 2005

4. Random Vibration & Shock Testing, Tustin, W., Equipment Reliability Institute, 2005

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