Impact and Drop Testing with ICP® Force Sensors

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Test engineers are often asked to provide 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 article 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 a required test system. Advances in ICP® quartz piezoelectric force sensor technology is discussed to show their benefit in impact testing.

Impact testing is performed to determine the energy absorbed or the energy required to fracture a unit under test (UUT). Take a straight-line collision like 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 to be produced and sold to consumers. Destructive impact testing may also be performed and recorded to document the strength or durability of nonsafety-critical items for industrial use.

Energy and Impact Force

During impact testing, design engineers usually like to know kinetic energy – an essential component to validate design criteria. The test engineer is challenged to obtain energy values by performing physical testing and using these data to calculate the results. A simple test method for measuring impact force versus displacement and then integrating the area under the force-displacement curve provides a measurement in energy units. However, what force output could the engineer expect to measure during the actual test?

The expected measuring range for a 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, the conservation-of-energy equation is:

$$mgh = 1/2\ mv^2$$

where:
m = mass
h = drop height
g = acceleration of gravity
v = velocity at impact

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

$$v = \sqrt{2gh} \qquad (1)$$

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.

$$W_{net} = 1/2\ mv_{final}{}^2 - 1/2\ mv_{initial}{}^2$$

In a drop test application, $W_{net} = 1/2\ mv_{final}{}^2$, since the initial velocity ($v_{initial}$) is equal to zero. Assuming one could easily measure the impact distance, the average impact force F is calculated as follows:

$$F = \frac{W_{net}}{d}$$

where d = distance traveled after impact.

The test engineer must estimate the distance traveled after impact to select an impact force sensor with the proper measuring range. Whether or not there is a perfectly elastic collision can affect the distance estimation and the resulting force calculation. (For the purpose of this article, 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 the impact force is minimized and is 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 it was originally dropped and absorbs very little energy. 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 (1 m).

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. Here we can employ Newton's 2nd law of motion, $F = ma$.

Using the final velocity calculated from the conversation-of-energy Equation 1, we may compute the resulting impact acceleration. This acceleration term depends on the pulse width of the force-time curve and must 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 are additive. The resulting peak acceleration may be calculated from:

$$a = \frac{V_{initial} - V_{final}}{t_{pulse}} = 2 \times \frac{\sqrt{2gh}}{t_{pulse}} \qquad (2)$$

It is important not to confuse 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:

$$F = ma \qquad (3)$$

Pulse width, and therefore 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 time. To compare the resulting impact

*Figure 1. Drop test system (*courtesy of Canadian Department of Natural Resources*).*

force calculation method of Newton's 2nd law of motion, three test materials have been tabulated in Table 2.

Drop Test Example

The Canadian Department of Natural Resources (DNR), CANMET facility, employs a team of specialists in mechanical, mining, electrical, computer applications, and electronic engineering.[2] Underground and open-pit mining involve a number of complex issues for the mining industry ranging from ensuring the safety of miners and the public to maximizing the recovery of ore reserves. Particular challenges are presented by mining under conditions of highly stressed or weak rock masses.

Test engineers at CANMET needed to test a specification for a ground support tenon that is used in the mining industry. After installation, the tenon is required to contain energy released from potential ground failures. A ground failure results in a shock wave that travels through the rock, resulting in an impact force into the tenon.

Table 1. Work energy method for obtaining force estimates by using displacements.

Material	h(m)	m(kg)	v_{final}(m/s)	KE(J)	d(m)	F(lbs)	F(N0
Steel	1	4.5	4.427	44.1	0.0001	99,137	441,000
Wood	1	4.5	4.427	44.1	0.1	99	441
Foam	1	4.5	4.427	44.1	5.0	2.0	9.0

Table 2. Newton's 2nd law method for obtaining force estimates using 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	18,050	80,294
Plastic	1	4.5	4.427	44.1	0.002	4,513	20,076
Crushable Foam	1	4.5	4.427	44.1	0.02	452	2,011

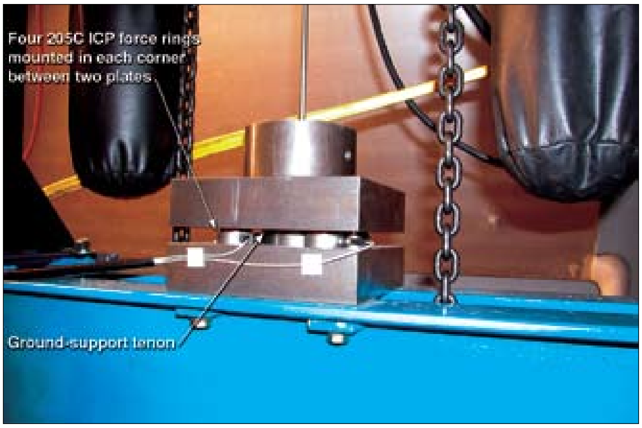

*Figure 2. Sensor mounting between two plates (*courtesy of Canadian Department of Natural Resources*).*

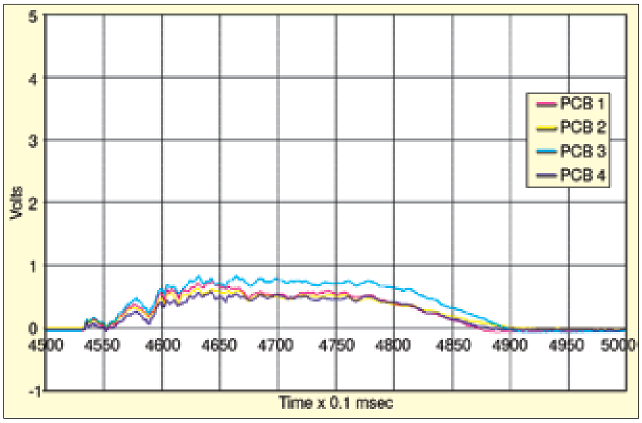

Figure 3. Force versus time history for a tenon.

The drop test system shown in Figure 1 is capable of dropping 6,600 lb (3,000 kg) from a height of up to 11 ft (3.4 m). A pair of 4,000 lb (1,800 kg) rated hoists raise the impact sled. Linear rails with metal shoes guide the test object onto the ground support tenon supported through an instrumented force plate on top of the headframe.

The impact plate is supported by four PCB Piezotronics Model 205C, ICP® quartz force rings, each having a 60 klb (267 kN) compression rating, for a total impact range of 240 klb (1,068 kN). Figure 2 shows a close up of the sensor mounting. The output of each sensor is routed to the BNC input jack on a PCB Model 484B06, sensor signal conditioner. All signal conditioner output channels, which initially provide independent DC signals, are then routed to a National Instruments data acquisition card, where LabView® software sums and then displays the output as a time waveform.

To select an impact force sensor, the DNR applied the principles in this article. One sample drop mass of 1257 lb (570 kg) was dropped from 59 in (1.5 m) with an estimated rock-to-steel pulse width of approximately 30 msec. Via Newton's Second Law force estimation method, this would result in 37,591 lb (167 kN).

$$v = \sqrt{2gh} = \sqrt{2 \times 386 \text{ in/sec}^2 \times 59 \text{ in}}$$
$$= \sqrt{45{,}548 \text{ in}^2/\text{sec}^2} = 213 \text{ in/sec}$$

$$a = \frac{2 \times \sqrt{2gh}}{t_{\text{pulse}}} = \frac{2 \times 213 \text{ in/sec}}{0.030}$$
$$= 14{,}200 \text{ in/sec}^2 \text{ or } 36.8\ g \text{ peak}$$

$$F = ma = \frac{w}{g} \times a = \frac{1257 \text{ lb}}{386 \text{ in/sec}} \times 14{,}200 \text{ in/sec}^2 = 46{,}242 \text{ lb}$$

Actual drop test data (Figure 3) were summed and resulted in a total peak force of 34,080 lb (152 kN) and a pulse width of 37 msec. Running this through our math model for Newton's Second

Law, we obtain an expected force of 37,600 lb (167 kN).

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 inaccuracies.

Although strain gage technology is commonly taught and widely used for impact testing, quartz piezoelectric force sensors provide technical advantages for this application. These sensors have stiffness a few orders of magnitude higher than strain gage load cells. They can easily measure to several tens of kHz. This is well beyond the ringing frequency of most strain gage load cells. Additional benefits of high stiffness piezoelectric 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, called a flexure, 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. For example, most strain gage load cells require a deflection of 0.001 to 0.003 in. (0.025 to 0.076 mm) 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 10 klb (450 N and 45 kN) full-scale range respectively.

Quartz piezoelectric 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 by sensors with internal ICP circuits. The high-frequency response of piezoelectric 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:

$$f_n \text{ in kHz} = 1/2\pi \times \sqrt{k/m}$$

where:
k = stiffness in N/m
m = mass in kg[4]

Piezoelectric 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 pulse width 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. Piezoelectric force sensor rise times may be estimated as one half of the natural period:

$$T_p = 1/2 \times (1/f_n)$$

where:
f_n = natural frequency
T_p = time to peak
For example, the PCB impact force sensor Model 200C50, with unmounted natural frequency of 30 kHz, has a rise time of 16 µsec.

ICP Force Sensor Configurations

Five force sensor configurations are commonly available and include general purpose, ring, impact, penetration and three-axis

Table 3. ICP® force sensor specifications.

Model	Range lbs (kN)	Sensitivity mV/lb (mV/N)	Stiffness lbs/µin (N/µm)	f_n, kHz unmounted
208C05	5,000 (22)	1 (0.22)	6 (1.05)	36
205C	60,000 (260)	0.08 (0.018)	40 (7)	50
200C50	50,000 (220)	0.1 (0.022)	97 (17)	30
208A22	100 (450)	50 (11)	5 (0.88)	18
260A11				
F_z	1,000 (4.5)	2.5 (0.56)	10 (1.75)	90
$F_{x,y}$	500 (2.2)	10 (2.2)	4 (0.70)	

Figure 4. PCB force sensor configurations.

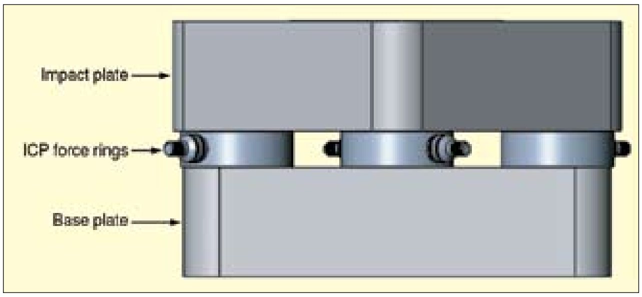

Figure 5. Side view of force plate assembly.

styles. A representative picture of each may be found in Figure 4, and key specifications are summarized in Table 3.

Piezoelectric impact force sensors are typically supplied with specially designed impact caps. The convex surface transmits impact loads evenly across the sensor, providing more accurate measurement 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 if the surface becomes damaged. These impact sensors, such as the PCB Models 208C05, 200C50 and 208A22, may be directly exposed to the UUT.

In cases like the ground support tenon, a larger force range and impact surface is required. So sensors with multiple force rings (PCB® Model 203B, for example), can be used in series between an impact plate and base plate as shown in Figure 5. 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.

When it is necessary to monitor the impact force simultaneously in three orthogonal directions, another sensor choice for single-impact events is the PCB 260 series, three-component force ring (see Figure 4). As with single-channel models, each x-y-z axis provides an independent AC 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.

Conclusions

Making impact force measurements is a proven way for test engineers to obtain the proper energy during an impact test. By assuming a perfect rebound for steel or estimating the pulse width for other materials, an engineer may use Newton's 2nd law to approximate the required force sensor range. Newton's math model can be used to select the proper force sensor measuring range.

Attributed to their high stiffness, quartz piezoelectric 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 a test engineer to easily obtain a required measurement.

References

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