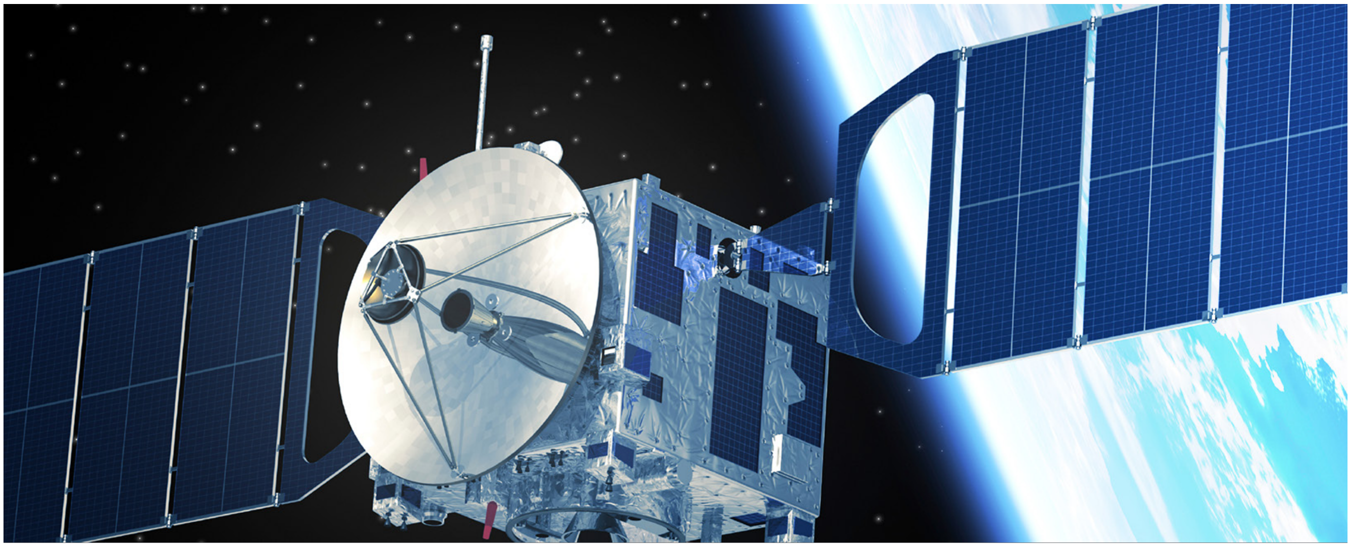

Optimizing 3-component Force Sensor Installation for Satellite Force Limited Vibration Testing

Written By
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ABSTRACT

Due to the high cost, long development times, and uniqueness of satellites, it has become imperative to implement techniques that ensure their safety during vibration qualification testing. Force Limited Vibration is used to limit the reaction force between the shaker and unit under test. The use of piezoelectric, 3-component force sensors facilitates easy and accurate measurement of the input force. This force relates directly, using Newton's Second Law, F=ma, to the "quasi-static" acceleration of the structure's center-of-gravity.[1][5]

Payloads are often fitted with piezoelectric force sensors using flight hardware or adaptor rings that present the problem of proper installation and preload required for a successful test. Preloading selection criteria is reviewed in detail along with its effects on gage sensitivity caused by bolt material effects. Case studies are presented showing 3-component piezoelectric force gages at each mounting point using flight hardware and factory supplied preload studs.

KEY WORDS: Force Limited Vibration Testing, Preload, Piezoelectric, Adaptor Ring, Force Link, Shunting, Stiffness, DC Coupled, Discharge Time Constant, ICP, CubeSat, NPSCul

PRELOADING AND MOUNTING OF PIEZOELECTRIC FORCE SENSORS

Preload Requirements

Piezoelectric sensors have exceptional linearity when properly mounted, with typical values of 0.5% Full Scale Output (FSO). Piezoelectric force sensors may be used at multiple incremental ranges up to their maximum measuring range. Therefore, selecting the proper force sensor really depends on the size and mechanical constraints of the device under test.

New users of piezoelectric force sensors for Force Limited Vibration Testing (FLVT) may sometimes become confused about how to mount and calibrate the sensors. There are two types of piezoelectric force sensors: 1) internally preloaded force sensors, referred to as force links and 2) externally preloaded force sensors, referred to as ring-style.

Internally preloaded sensors do not require any preloading, while the ring-style sensors require preloading during installation. Ring-style sensors must be preloaded to approximately 20% or more of their measuring range in order to obtain the best possible linearity. This linearity is achieved by tightly clamping the internal components, piezoelectric material and housing, together. Figure 1 shows the region of linear output with proper preload. The preload also acts to limit slippage of the sensor caused by side loads experienced during use.

Tension measurements are also possible if the force sensor has been mounted with additional preload. The preload must be sufficient enough to allow the ability to measure tensile and compressive loads.

Preloading is also required for shear force measurements using 3-axis force sensors. Friction is required between the force sensor and mating surfaces in order to transmit the shear forces. The required preload force is calculated as:

Equation 1: $\mathbf{F_{preload} = F_{shear} \div \mu}$ where μ is the coefficient of friction

A typical value for μ is 0.13. The required preload is at least 7.7 times the desired shear force. PCB recommends 10 times the desired shear force for a safety factor that provides a margin of two for preventing gross slip, thus preventing "micro-slip" during shear force measurements.[6]

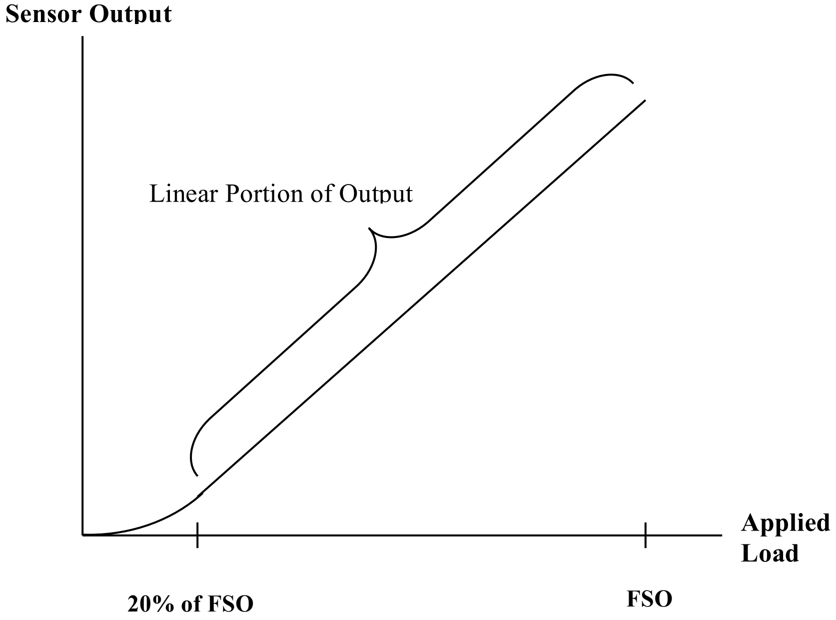

Figure 1
Output vs. Preload Force

Preload Hardware

Force rings that require preload are calibrated and shipped with a standard mounting stud. This stud is specially designed to stretch, yet still maintain a very high tensile strength, beyond the force ring measurement range. The stretching action of the stud is designed to allow the force ring to maintain the greatest sensitivity possible. The stiffer the stud becomes, the more force it takes away from the sensor, and effectively reduces the force ring output. The standard stud (Figure 2) is made of beryllium copper (BeCu) and shunts approximately 5% of the force.

Steel bolts can take approximately 20 to 50% of force. Different bolt materials may be used as shown in Figure 3 on an instrumented horseshoe, but the sensor requires recalibration with the new bolt.
In one case, a horseshoe was instrumented and preloaded with steel bolts (Figure 3). The corrections of the individual sensors sensitivities were between 4.4% and 12.8% smaller than those provided on the factory calibration certificates. [2] Correction for the sensitivity of the entire horseshoe was only necessary for the z-axis, the x and y axes have a negligible change with bolt material. This is because the preloaded bolt is not stretching in the x-y direction. As mentioned above, the friction created by the preload is responsible for force transmission.

Figure 2
BeCu Preload Stud Kit

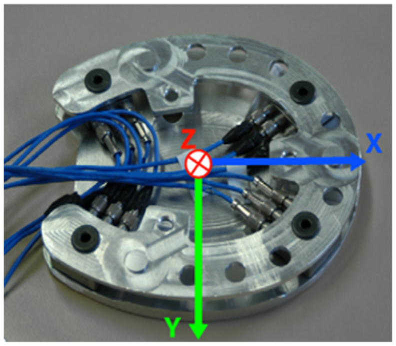

Figure 3
Instrumented Horseshoe with Steel Bolts

Also of importance, in preload and subsequent calibration, is the method in which the threads couple to the unit under test. Preload studs in adaptor rings or flight hardware bolts are usually used in a manner where the plate on top of the 3-component force ring has a clearance hole which the stud or bolt passes through. In the installation shown in Figure 4, the stud or bolt is not directly connected to the top plate by its threads; therefore it does not shunt any force.

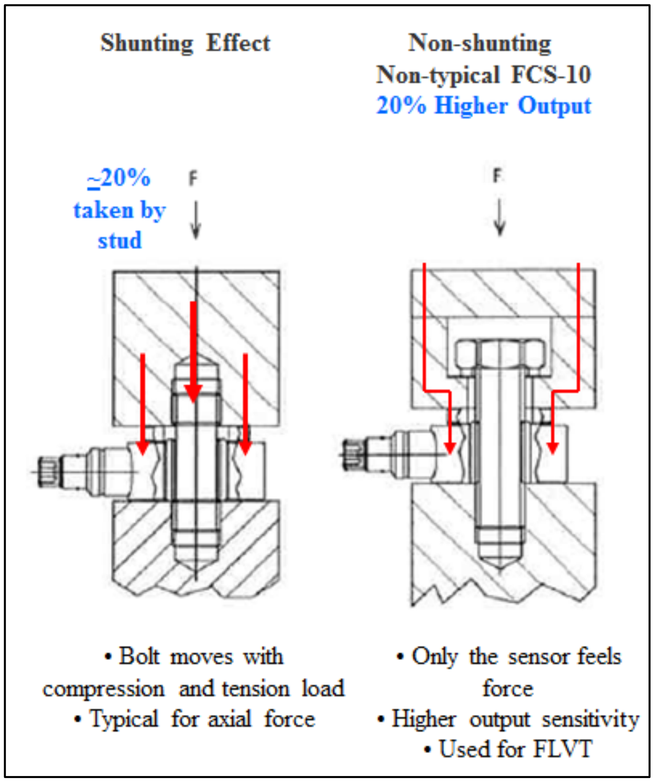

Figure 4
Preload Stud Thread Engagement Examples

Preload Calibration Effects

A calibration study was performed using an ICP® 3-component force ring, PCB Model 260A01. The purpose was to determine the sensitivity correlation between the shunting and non-shunting (FCS-10) preload methods. The non-shunting method was similar to that used for FLVT test on the James Webb Space Telescope NIRSpec bracket assembly at Utah State Space Dynamics Laboratory (Figure 5).[3]

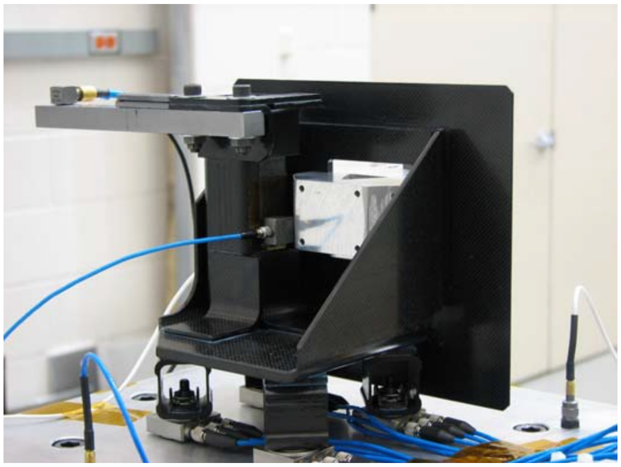

Figure 5
James Webb Space Telescope NIRSpec Bracket Assembly

Three units were selected and mounted in two configurations, with and without shunt effect. Each sensor was preloaded to the recommended 5,000 lbs. required to obtain full-scale x and y-axis force ranges of 500 lbs. The mounting arrangement for shunt calibration is shown in Figure 6, where the load was applied in the vertical direction via a precision strain gage reference load cell. In the +z-axis (compression direction), force enters through a ball bearing to account for misalignment and then through a preload nut.

Figure 6
Shunt Method Calibration
Z-axis Force Application through Threads (Left), X-Y Axis across Bolt (Right)

The results in Table 1 show that the force path in the z-axis is shunted approximately 13% through the threads of the nut before reaching the sensor. In the case of the x and y-axes, the friction created by preload keeps the upper and lower sensor plates from sliding and making contact with the preload bolt. There is little, to no corresponding shunt effect, since the bolt does not make contact with the sensor. Additionally, the preload bolt is generally softer in the later x and y-axes due to bending. [6]

Table 1
Sensitivity of "Typical" & Non-Typical" Mount Model 260A01

SN	Axis	Sensitivity mV/lb. Shunt in Typical Mount	Sensitivity mV/lb. Non-shunt, Non-typical Mount FCS-10	Amount of force shunt
6	x	9.73	9.88	2%
	y	9.82	9.90	1%
	z	2.56	2.94	13%
22	x	9.95	9.92	0%
	y	9.74	9.86	1%
	z	2.48	2.86	13%
4	x	9.91	9.93	0%
	y	9.76	9.82	1%
	z	2.47	2.86	14%

It has long been stated in Section 4.4 of NASA-HDBK-7004C that, "The sensitivity of the installed configuration is equal to the sensitivity of the transducer itself multiplied by the ratio of the transducer stiffness to the sum of the bolt plus the transducer stiffness."[1]

Using this concept, the ratio of the force seen by the gage to the total force condition of the gage, plus bolt, is given by the corresponding ratio of stiffness shown in Equation 2.

Equation 2: Force Ratio = K gage / (K gage + K bolt)

The gage axial and lateral stiffness's are provided in the gage's specification sheet, with typical values from 10 to 40 lbs./µin. Since the gages are relatively stiff, any compliance in the gage load path should be included in the calculation.[6]

PRELOAD EXAMPLES

Adaptor Rings

A CubeSat launcher (NPSCul) was prepared for FLVT at the Naval Postgraduate School in Monterey, CA. The NPSCuL is a five-sided structure capable of carrying up to 24 CubeSats to orbit. The vibration test environment for CubeSats flying on NPSCuL is rather harsh, based on the Atlas-V launch vehicle. An adaptor ring (similar to the cutaway view shown in Figure 7) consisting of four Model 260A03 ICP® 3-component piezoelectric force rings was prepared in order to adapt the NPSCuL to the shaker table (Figure 8).

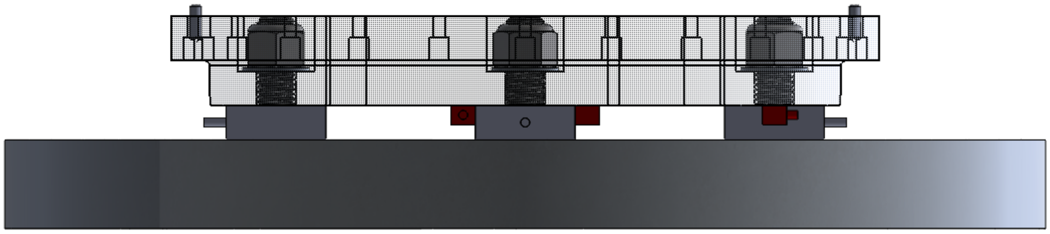

Figure 7
Typical Section View of Instrumented Adaptor Ring
Courtesy of Skybox Imaging, Inc.

Preload for this application was 35,000 lbs., and was maintained within 5% of each other by increasing the preload incrementally until the preload for each sensor was within the desired tolerance. In order to obtain such high preload values, a large extendable handle wrench was required to maintain smooth application of torque, and in this case a 5 ft. extension was used. The force ring was connected to a DC coupled signal analyzer and the voltage was converted to a force using the factory calibration sensitivity. Voltage increase was measured each time a sensor's preload nut was torqued and then tracked in an excel spreadsheet. This process was repeated ten times incrementally to achieve uniform application of the desired preload across all four force rings. It was found that torquing one sensor in small increments had a negligible effect on the preload of the other three sensors.[4]

During dynamic sensitivity verification, it was found that the factory sensitivity of the sensors (using the FCS-10 non-standard preload method) remained valid. For the verification method, data was used from a low level sine sweep with the NPSCuL structure mounted to the FLVT setup on the shaker. The sweeps were conducted at 0.25g and 0.5g between 20Hz - 2000 Hz. The first fundamental frequency of NPSCuL is ~48 Hz. The transfer function between the force measured and the control acceleration was used to give the apparent mass during the sine sweep. At frequencies below the first fundamental frequency of the article, the motion is estimated as rigid body, therefore the entire mass of NPSCuL was considered to be moving as a rigid body. This means the value of the transfer function mentioned above should give the mass of all the hardware above the force sensors. It was determined experimentally that the measured mass for preload values between 30k-35k lbs., was within 5% of the expected mass of the items above the force sensors, and anything less would exceed 5% error. [4]

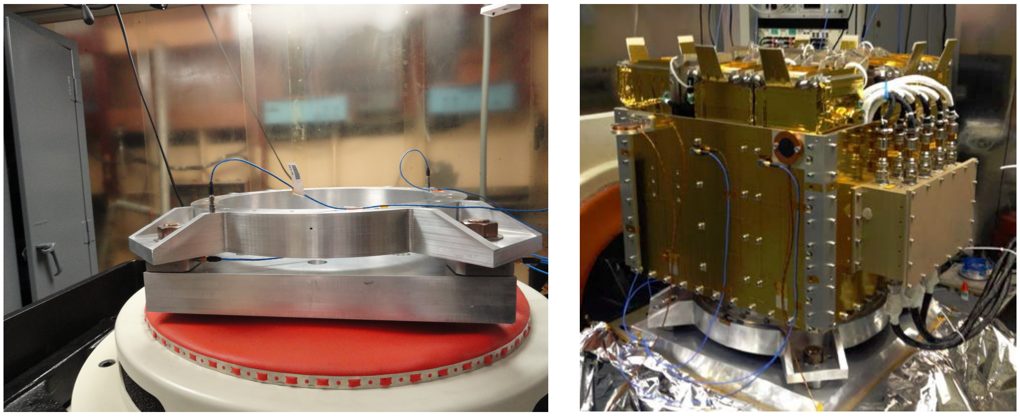

Figure 8
Naval Postgraduate School
FLVT Preloaded Adaptor Ring (Left) and OUTSat Acceptance Test (Right)

Force Links

A piezoelectric 3-component force link, similar to that shown in Figure 9, eliminates preload requirements of 3-component force rings. It offers a convenient; four screw hole mounting plate on each end the sensor. Force links are constructed by installing a 3-component force ring sensor, under preload, between two mounting plates.

Figure 9
Model 261A03 ICP® 3-component Force Link

An elastic, BeCu stud (Model 081M75 in Figure 9) holds the stainless steel assembly together. The use of this elastic stud permits the applied force to be sensed by the crystals with a minimal amount of shunted force. The stud also provides the necessary normal force, and thus friction required to transmit shear forces in the x and y-axes. Since 3-component force links are factory preloaded, they may be used for measurements of compression and tension in the z-axis, and positive and negative shear forces in the x and y-axes.

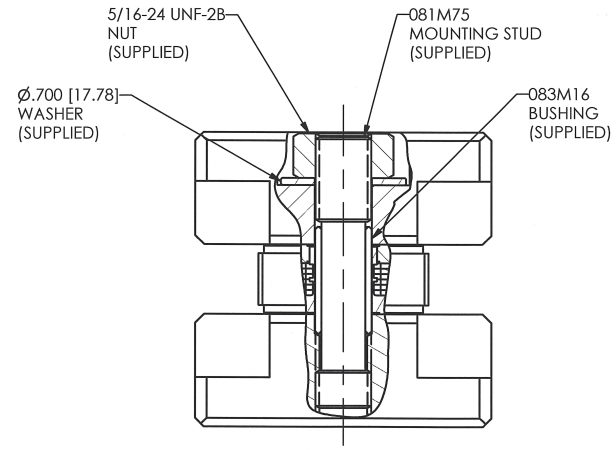

Figure 10
Section View of Model 261A03 ICP® 3-component Force Link

The force link is similarly assembled and preloaded like adaptor rings used in the NPSCuL. The preload stud Model 081M75 shown in Figure 11 is screwed into the base plate and the pilot bushing Model 083M16 is installed over the center section of the stud. The internal force ring is lowered over the pilot bushing, followed by the top plate. Prior to preloading, thread locking epoxy is applied to the stud threads to ensure no loss of torque after the preload process is complete.

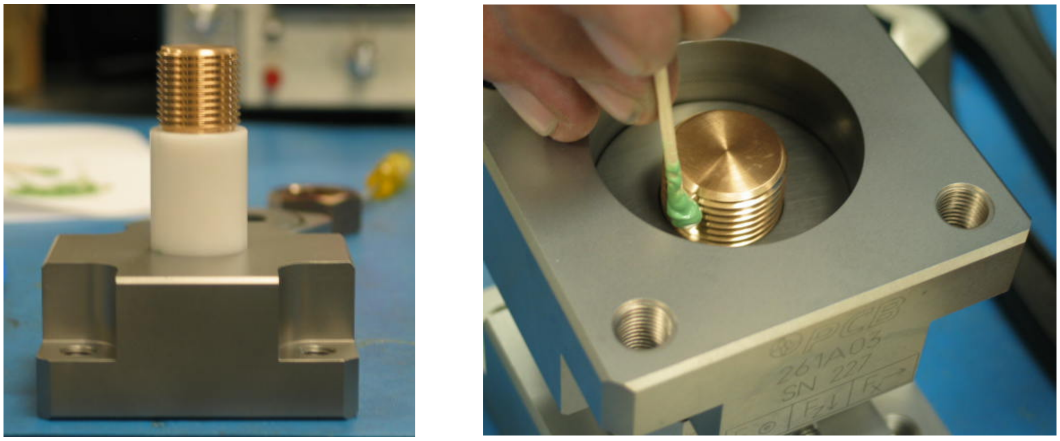

Figure 11
Preload Stud/Pilot Bushing Installation (Left), Thread Locker (Right)

SIGNAL CONDITIONING REQUIREMENTS

Low frequency response is determined by the electrical characteristics of the quartz piezoelectric force sensor. Preloading has a time limitation that is set by the system Discharge Time Constant (DTC) for ICP® force sensors or drift rate for charge output sensors. DTC is defined as the time required for an electrical signal to discharge exponentially to 37% of the original value, whereas drift rate is a function of leakage current across a transistor in a charge amplifier.

The low frequency response for quartz piezoelectric force sensors looks like a high-pass filter. The point where the frequency response falls off, known as the cut-off frequency, is set by the system DTC. Points at -3 dB, -10%, and –5% in the frequency response curve may be calculated as shown in Figure 12. Within this low frequency end of the sensor response is where quasi-static measurements can be made with a sufficiently long DTC.

Figure 13 shows the response of two quartz piezoelectric force sensors when a steady state load is applied and maintained. It becomes clear that the signal from a lower DTC value of 10 seconds dissipates faster than a signal with a higher DTC of 500 seconds.

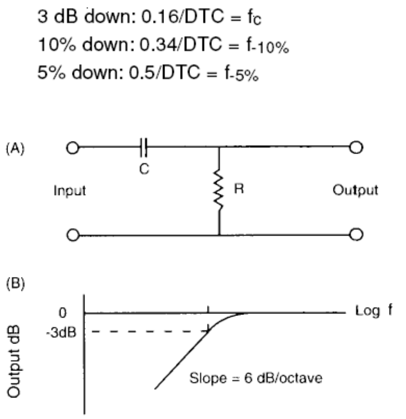

Figure 12
Low Frequency Characteristic
of a First-Order, High-Pass Filter

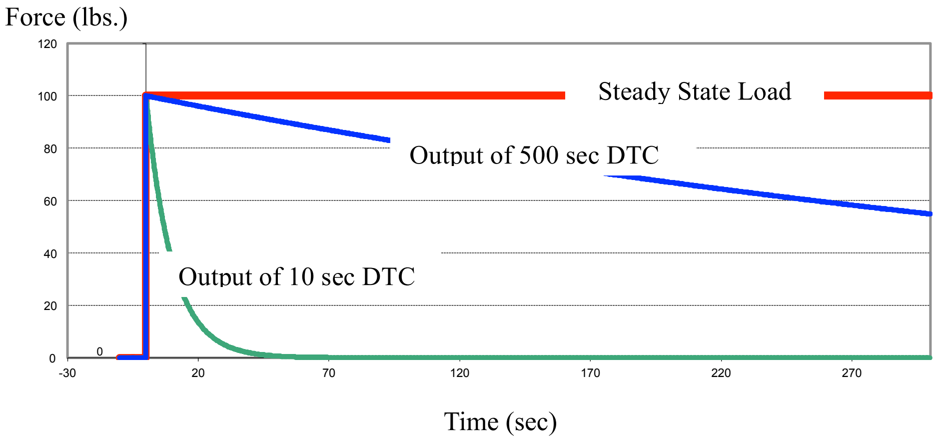

Figure 13
Discharge Time Constants

When preloading ICP® output sensors for static calibration, DC coupled signal conditioners, such as PCB® Model 484B series, and a DC coupled readout device should be used. They allow the sensor's DC bias voltage to be zeroed and do not apply any additional high-pass filter effects to the system. A general rule of thumb for such measurements is that the output signal loss and time elapsed over the first 10% of a DTC have a linear, one-to-one relationship, as depicted in Figure 14. Thus, in the first one-hundredth of the DTC, there will be only 1% signal loss. If a sensor has a 2,000 second DTC, over the first 20 seconds, 1% of the original input signal will decay.

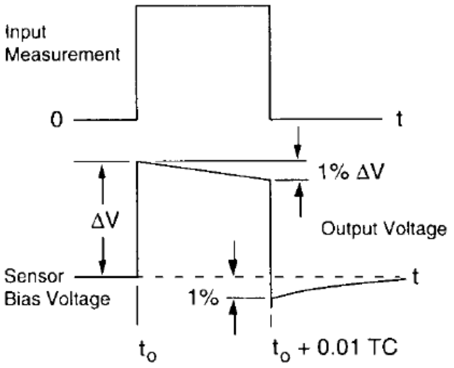

Figure 14a
DC Coupled Piezo Response
to a Static Step Input

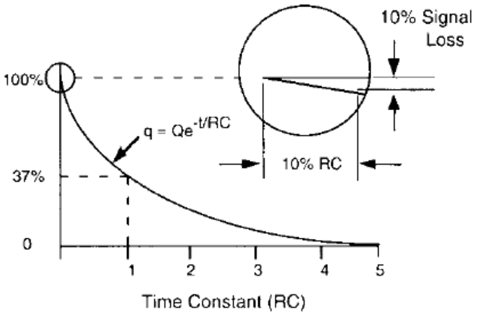

Figure 14b
Linear Portion of a DC Coupled
Discharge Time Constant

For example, when a 1,000 lb. static load is applied to a DC coupled force sensor that has a 2,000 second system DTC, within the first 20 seconds (1% of 2,000) the force output signal would decay 1%, or less than 10 lbs. So for 1% accuracy, the reading must be taken in 1% of the DTC, or 20 seconds. The entire system must be DC coupled, both signal conditioner and readout device, which means the sensor has a long DTC.

SUMMARY

Proper test planning for 3-component force sensor use is vital to a successful FLVT. The test engineer must consider the effects of various preload values, shunting and non-shunting mounts and differences in the stiffness of preload bolt materials.

Preload is required for linear operation of the gage, tension measurement and to create the necessary friction to allow for shear force measurements. Direct loading of preload stud threads versus a clearance-hole arrangement will alter the gage sensitivity during in-situ dynamic calibration. Force link gages allow for ease of use and do not require preload, however they do add to the apparent mass of the device under test and must be considered during dynamic test work.

As large adaptor rings require multiple sensors to be preloaded in small increments, DC coupling capability of signal conditioners analyzers becomes critical for the steady state signal requirement during preloading operations.

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BIOGRAPHY

Bob Metz holds a BS degree in Aeronautical and Astronautical Engineering from Ohio State University and a MBA from State University of NY. Bob has been an instrumentation engineer for 19 years, focusing on vibration, pressure and force measurement using piezoelectric sensors. He is currently Director for the Aerospace & Defense Division of PCB Piezotronics, Inc. Bob can be contacted via email at bmetz@pcb.com.

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