EDITORIAL

Ongoing Struggle to Measure Mechanical Shock in High-Energy Environments

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The following is a condensed history of the evolution of high-g shock accelerometers that I have witnessed in their development over nearly 50 years. This vantage point encompasses 30 years inside a nuclear weapons lab (Sandia National Laboratories) and 18 years as both an engineering professor and a consultant to sensor manufacturers and their customers.

I'll begin by sharing a story that an associate at Sandia (Loyt Lathrop) told me in the late 1960s or early 1970s time frame. Loyt related how in the 1950s, they would perform rocket sled tests at Holloman Air Force Base with the sleds instrumented with Statham unbonded strain gage accelerometers. Piezoelectric accelerometers were in their infancy at that time. He related how, when reviewing the telemetered data from the tests, he never knew if he was looking at the vibration of the sled or the vibration of the filaments in the vacuum tubes of the accelerometer signal conditioning! Progressively, beginning with the first piezoelectric accelerometer (B&K, 1942), test engineers transitioned from metal strain gage type accelerometers to the more rugged piezoelectric type.

I made my first acceleration measurement in 1965 using an Endevco 20,000 g accelerometer with a 100-kHz natural frequency conditioned by a Keithley cathode follower (vacuum tube amplifier). Charge amplifiers had been patented in the U.S. in 1962 but were not yet universally available. During the '70s, piezoelectric accelerometers began to be commercially available in ranges to 100 kg. However, an anomaly associated with their contained ferroelectric ceramic elements continually displayed itself at high g levels. A non-return to zero would be present at the end of energetic shock events measured with accelerometers containing these piezoceramic elements. Alternatives to piezoelectric accelerometers for severe shock were few.

In the 1969-70 time frame, Dave Davis at Sandia Labs initiated an effort to determine the cause of this non-return to zero (zero shift). He requested the assistance of a chemist by the name of Ralph Plumlee, and I helped with the associated testing. In 1971, Ralph published a 61-page tech memo detailing the idiosyncrasies of the ferroelectric ceramics at stress levels such as those that occurred at accelerometer resonance excitation. Domain reorientation of dipoles in the ceramic material was found to occur. This finding directed an application focus toward single-crystal piezoelectric materials, specifically the quartz type from Kistler and PCB.

The Kistler 805A (designed about 1966) subsequently functioned well for a number of years on Sandia's accelerated shock machines. However, its operational threshold was eventually reached due to relative motion (slippage) in its quartz crystal stack. Thus, zero shift recurred, but for another reason.

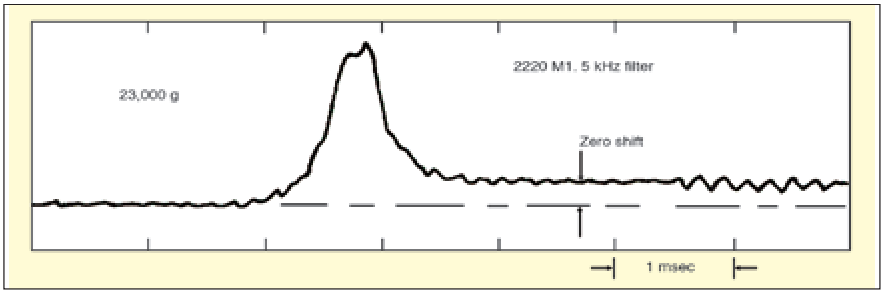
In 1971, an evaluation was performed on another quartz accelerometer. The focus was a new, specifically designed PCB model 305M23. By this time, electronics had moved inside of piezoelectric accelerometers (IEPE = integral electronics piezoelectric, ICP® a PCB trademark). The 305M23 took advantage of the presence of an active electrical component within the accelerometer to create the first IEPE 100,000-g accelerometer, which also contained a two-pole, low-pass filter. At least within Sandia, this resulted in the first successful Hopkinson Bar evaluation (Fred Schelby) of a high-g shock accelerometer.

Later in the early '70s, after a joint evaluation series at Sandia, Bill Shay (a longtime colleague) at Lawrence Livermore Laboratory selected the model 305A (non ICP® version of the 305M23) for a lengthy series of conventional, multi-warhead munitions tests against hardened targets. Bill achieved limited field success. At this time, piezoelectric accelerometer technology still needed more development before becoming routinely reliable in the highly energetic environments (cannons, penetrators, etc.).

In 1970, Lawrence Livermore Laboratory funded Endevco to develop a diffused semiconductor gage for integration into an accelerometer (Model 2266) intended to operate in radiation environments associated with underground nuclear tests. Pierre Fuselier and Bill Shay, again at Livermore, were development collaborators, and a Sandia staff (Dave Overmier) became interested in fielding these devices. Overmier placed the 2266 on tuning forks in an underground nuclear test and they worked extremely well to 10s of thousands of gs without any zero shift – a pleasant surprise! So an increased focus was placed on piezoresistive (PR) technology for severe shock.

My work continued to include supporting nuclear effects testing, and Joe Quintana, a next-door neighbor at the Air Force Weapons Lab (Kirtland AFB), was involved in missile silo hardening. So a lot of accelerometer performance information was exchanged between Sandia, Kirtland, and the Livermore team. A non-radiation-hardened version of the Model 2266, but geometrically identical, was requested from Endevco in this same time frame in ranges to 50 kg, the Model 2264. Prior to this, Bytrex had been somewhat of a competitor of Endevco in piezoresistive accelerometers at Kirtland, but one disastrous test series eliminated them from this position. So because the physics of silicon crystals had no mechanism to produce zero shift, for a number of years the 2264 was a workhorse at all three laboratories.

In 1988, Anthony Chu of Endevco developed the first mechanically isolated piezoelectric accelerometer with electronic filter (7255A). Its intent was to mitigate the high-frequency resonance of the accelerometer. This would minimize overstressing of the ceramic element and eliminate dipole reorientation and zero shift. His design was subsequently shown to be nonlinear, but his idea proved to be a catalyst for others to follow. PCB did not manufacture piezoresistive accelerometers, so they (Jeff Dosch) too became interested in developing a series of high-shock, mechanically isolated and electrically filtered, piezoelectric accelerometers (e.g., 350B02).



Zero-shift record, circa 1970.

Prior to Chu's work, the introduction in 1983 of the MEMS (all silicon) based Model 7270A accelerometer (Bruce Wilner, Endevco), in ranges to 200,000 g with a 1.2 MHz resonant frequency and a mass of only 1.5 grams, had provided a significant improvement in test measurement capability. However, its chief limitation was that its silicon flexure resulted in a very high "Q" at resonance as compared to ferroelectric or quartz accelerometers (10 to 20 times higher). So the accelerometer remained susceptible to breakage (silicon is brittle) at high frequencies. Bob Sill, then employed at Endevco but now PCB, was heavily involved in the 7270A accelerometer development and testing. Aberdeen Proving

Ground, Sandia, Kirtland, and others quickly became customers.

At Sandia, for both the 2264 and the 7270 models, Tom Baca and Dave Martinez developed a procedure to bond the accelerometers to the test item with a specific polysulfide rubber to minimize breakage. This procedure was coordinated with Sandia's Plastic Shop to control bond thickness and adherence. Subsequently, Vesta Bateman took this process to a much more sophisticated level at Sandia with her development of a captive and highly characterized and effective isolator for the 7270. She then transferred this technology to Endevco (7270M6).

During the early 1990s, the Cold War had ended and high-shock accelerometer development had largely stagnated. In the latter part of the '90s, Dick Mabry at the Air Force Fuze Branch (Eglin AFB), with assistance from Alain Beliveau, was attempting to develop accelerometer-based fuzes for smart munitions and was having only marginal success. Like all new programs, this was supposed to be a "low-cost" effort and the initial attempt was to use an inexpensive piezoelectric engine knock sensor. Not surprising, zero shift was rediscovered!

In 1998, Tom Seng (who coordinated much of this activity) and Bob Clark of Endevco and I visited both the Fuze Branch and their contractor Alliant Tech. I took along Plumlee's 1971 report. In short order, the report was copied and forwarded to our UK Allies. Because of zero shift and the need for recording long pulses, the 7270A became integrated into fuzing activities. However, the breakage issues again soon became a challenge.

At a follow-up meeting at the Fuze Branch, the same players, but with the addition of Bob Sill, identified deficiencies in the 7270A, and these were summarized. With a viable Air Force program, accelerometer design improvements were proposed. About this same time, Endevco was reconfiguring itself internally as a company, and this proposal did not move forward.

In CY 2000 a contract was placed with me, now at the University (Texas Christian University), to look at smart fuzing methodologies for the USN (China Lake, Dave Riggs). Walt Williamson, ex-Sandia, had joined me at TCU and we collectively completed this work in the summer of 2002. During this work, at a meeting at Endevco with Larry McCormick, Bob Sill and I discussed the desirability of incorporating some small amount of damping into MEMS accelerometers. Bob subsequently elegantly designed and implemented the MEMS design improvements discussed at the earlier Eglin meeting, as well as integrated the desired light damping (via squeeze film), not at Endevco, but now while employed at PCB (PCB Models 3991 and 3501).

During this same period, ongoing work by Anthony Agnello improved PCB's series of linear, mechanically isolated piezoelectric accelerometers (350D02). Both of these items are reported on in a subsequent article in this issue of S&V. The article describes the current state of the art or "current technology" for shock accelerometers. The competitiveness is high among sensor manufacturers, and Endevco is at this time introducing a MEMS accelerometer similar in specifications to Bob Sill's recent development.

What I have just described summarizes almost 50 years of the continuous evolution of high-shock sensor capability. Has success been achieved? Let's return to the story I shared in the first paragraph of this editorial relayed to me by Loyt Lathrop. By contrast, in recent years I witnessed a 155-mm gun test at the Air Force Fuze Branch while visiting with Alain Beliveau. A 155-mm projectile with contained data storage capability was fired though a block of concrete. A backhoe immediately dug the projectile out of a dirt catcher, and within two hours we witnessed the 10s of thousands of gs the accelerometer in the projectile had measured as it penetrated through the concrete block.

This editorial has summarized shock accelerometer development up to the current technology described in this issue of S&V. There is no "magic bullet" for highly energetic shock measurements. Improvement in capability is steadily occurring, but as each new sensor development increases capabilities by 15%, customer requirements increase by 30%. However, technology is moving forward both in MEMS and isolated piezoelectric technology.

At this point it's noteworthy to comment that any accelerometer only measures what is input to its base. In the rush to "record something," this fact often becomes overlooked. The mount and its characterization are exceedingly critical. As I note in the previouly referenced S&V article in this issue, the accelerometer experiences six degrees of motion in application. Characterization of the accelerometer on a Hopkinson Bar under basically one-dimensional motion is only a first approximation as to how it will perform in the test environment. In addition, accelerometers continue to be miniaturized and become capable of responding to higher frequencies. Never forget that acceleration is a point measurement, and even the miniature accelerometers available today modify structural response at very high frequencies ("How High in Frequency are Accelerometer Measurements Meaningful," Walter, SAVIAC, 2008).

In presenting this history, other notable players have been omitted. For Example, Scott Walton at Aberdeen Proving Ground made significant advances in measuring ballistic shock. However, his measurement tools were the same as those described in this editorial. Today, most of the customer-driven, high-shock accelerometer development is centered with Alain Beliveau, Jason Foley, and Janet Wolfson at the Air Force Fuze Branch. I hope that they and future customers continue to drive the industry forward. S/V

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