The History of the Accelerometer

1920s-1996 – Prologue and Epilogue, 2006

Patrick L. Walter, Texas Christian University, Ft. Worth, Texas

Upon receiving his undergraduate degree from Penn State in 1965, Patrick Walter (right) began 30 years of employment at Sandia National Laboratories in Albuquerque, NM. While on roll, Sandia sponsored his M.S. degree at the University of New Mexico and his Ph.D. degree at Arizona State University.

Dr. Walter's first position at Sandia was as a test engineer in environmental testing, which encompassed shock and vibration. Subsequently, he worked on instrumentation development for flight, field, and laboratory testing. The majority of his tenure was spent managing various test activities. Many of these management assignments ran concurrently and included: experimental mechanics, test facility development, mass properties, transducer calibration, measurement consulting, telemetry component development, telemetry system packaging (including "bunker busters"), and inertial test system development. Later in his career he managed a rocket launch facility in Kauai, HI and also developed launch systems for flights from Sandia and NASA operated facilities. His last assignment involved establishing a program at Sandia under contract to the Federal Aviation Administration to enhance the structural inspection of aging transport and commuter aircraft.

In 1995, Dr. Walter joined the engineering department of Texas Christian University and subsequently served an interim period as Department Chair. At TCU, Dr. Walter has developed the solid and structural mechanics laboratories as well as the electro-mechanical design sequence. Included among the companies that have provided annual support for this design sequence are: Lockheed-Martin Aeronautics, Bell Helicopter Textron, Alcon Laboratories, U.S. Army Engineer and Development Center Waterways Experiment Station (WES), Aberdeen Proving Grounds (U. S. Army), and PCB Piezotronics. In 2001 TCU's Design Laboratory won first place nationally in a competition sponsored by *Design News* and ANSYS among all universities.

Through TCU Dr. Walter also teaches a continuing education program in Measurement Systems Engineering, which has been presented throughout the U.S., Canada, and overseas. In 1996 he established Test Measurements Engineering, a technical consulting firm in measurement system design focused on the aerospace and defense community. Since 2003, concurrent with his TCU responsibilities, he has been extensively associated with PCB Piezotronics, Inc. as their Measurement Specialist.

Dr. Walter has numerous publications and has served and chaired DoD and DOE committees. He is a member of ISA (25+ years, Aerospace Systems and Test Measurements Divisions), Society of Experimental Mechanics (also 25+ years), and American Society of Engineering Educators (Instrumentation Division). He is also a Contributing Editor on the masthead of *Sound and Vibration*. He is a licensed Professional Engineer in the state of New Mexico.

Prologue

Researching and writing the following article ten years ago (1996) was professionally very satisfying. The fact that its accuracy has not been challenged during that time period indicates that it should continue to withstand the test of time for validity. It is a pleasure to report that all eleven individuals in the photo of Figure 6 are still alive and healthy, and seven are at least still partially involved with accelerometer technology. The senior member of that group, Walter P. Kistler (age 88), is still actively involved in scientific endeavors. Mr. Abe Dranetz (age 84), who built the first practical, commercial, piezoelectric accelerometer in the United States, remains active in philanthropic affairs. Prof. Emeritus Peter K. Stein (Arizona State University) recently received the Shock and Vibration Information Analysis Committee's Lifetime Achievement Award. Mr. Jim Lally (C.E.O. of PCB Piezotronics, Inc.) recently received the D. J. DeMichele Award of the Society for Experimental Mechanics.

I have identified a few, minor, corrections or additions to the article that I wish to identify: (1) Dytran was described as a "PCB spin-off." More accurately, Mr. Nick Change, Dytran founder, began work at Kistler Instruments in 1965, held managerial positions at PCB from 1971-1978, rejoined Kistler for a year, and then initiated Dytran in September 1980. (2) The contributory work of both Mr. Verne Siegel and Mr. Bob Lally in integrating MOSFET technology into quartz sensors within Kistler Instruments in the mid-1960s should have been mentioned as it assisted the Kistler patent filing. While the genesis of this work may have been in an earlier U.S. patent 3,294,988, the work at Kistler Instruments in the 1960s clearly moved this technology into the piezoelectric transducer marketplace. (3) A 1967 paper by Mr. Bob Lally,[18] PCB co-founder, is cited as it provides an early technical description of this MOSFET technology, as well as additional historical references. (4) Clevite Electronic Components division of Clevite, Inc., (previously Brush Development then Brush Electronics) Cleveland, OH, was a respected manufacturer of piezoelectric accelerometers in the late 1950s and early 1960s that subsequently vanished.

Since this writing, no evidence has been found of any type of accelerometer having being used before the early 1920s. The use of quartz and tourmaline piezoelectric pressure transducers has subsequently been verified as early as 1919.[19]

With these additions and clarifications, and the recognition of Vibro-Meter, Inc. (high temperature engine vibration focus), not mentioned in 1996, this article covering 73 years of accelerometer development is again presented as originally written. Its *Epilogue* will provide the history of the past ten years of accelerometer development (1996-2006), as well as a vision of the future direction of accelerometer technology.

1920-1996

This article summarizes the history of accelerometer development and the subsequent evolution of the commercial accelerometer industry. The focus is primarily on piezoelectric and piezoresistive accelerometers, although early resistance bridge type accelerometers are also described. The pioneer accelerometer manufacturing companies are identified and a chronology of technology development through 1996 is presented.

The earliest development of the resistance-bridge-type accelerometer, which was ultimately commercialized, is credited to McCollum and Peters.[13,17] It weighed about a pound and was 3/4 × 1-7/8 × 8-1/2 in. in size. It consisted of an E-shaped frame containing 20 to 55 carbon rings in a tension-compression Wheatstone half-bridge between the top and center section of the frame. Figure 1 illustrates this device. By 1923 it had found application in bridges, dynamometers, and aircraft. By 1925 its associated technology had moved to Germany and in 1927 it was commercialized in the U.S. through Southwark, later Baldwin-Southwark, and now BLH Electronics. Its reported resonant frequency was less than 2000 Hz. By 1936, Southwark Bulletin 132 advertised[13] a two-axis accelerometer model with "adjustable cork damping" in ranges to 100 g. Reported applications were: "recording acceleration of an airplane catapult, passenger elevators, aircraft shock absorbers and to record vibrations of steam turbines, underground pipes and forces of explosions . . ." In addition to eight overseas users, 110 U.S. users were identified who apparently were willing to pay the early 1930's price of $420!

Additional insight into the early uses of accelerometers can be acquired from F. G. Tatnall's book *Tatnall on Testing* printed by the University of Pennsylvania Press (1966). Tatnall's professional career began with his graduation in 1920 from the University of Pennsylvania and spanned in excess of 40 years of experimental mechanics development and testing. He reflects in his book that, during the depression years in the United States, all advancement of testing seemed to reside at the Washington Navy Yard and the Naval Aircraft Yard at Philadelphia. During this period, drop tests of airplanes are described which required "electric pressure gages for the oleo gear, together with accelerometers and deflection transducers mostly made with inductor telemeters and slide wires."

Resistance Strain Gages

Large scale commercialization of accelerometers, however, likely awaited the advent of the bonded resistance strain gage. The discovery of the strain gage is independently credited to both Arthur Ruge, Massachusetts Institute of Technology (MIT), April 3, 1938, and Edward Simmons, Caltech, September 1936.[1] The first quantity order of 50,000 strain gages from a business that Ruge established with A. V. deForest in 1939 occurred in 1941. Even before this date, aircraft manufacturers such as Douglas Aircraft were manufacturing strain gages for their own use. Just months after the invention of the strain gage at MIT, J. Hans Meier constructed the first strain gage accelerometer while working there. His "Elastic Dynamometer" contained bonded wire filaments on four supporting strips supporting a steel block weighing 3.434 pounds.[13] It measured 2 g, 4 Hz vibrations supporting the study of earthquake effects on a water tower. Tatnall further states that it was in the early 1940s when strain gage load, pressure and acceleration transducers "made their complete and magnificent debut in flight." This was in conjunction with cannon firing on the twin-tailed P38 aircraft and resulted in "miles of oscillograph records."

Louis Statham (1907-1983) subsequently performed experimental work at Curtiss-Wright Research with unbonded wire strain gages and went on to pioneer a transducer manufacturing firm using this technology, Statham Instrument Company, in Los Angeles, CA, in 1943. Statham's strain gage accelerometers found application in many dynamic test applications. Given Ankeny Brewer, in his book *Practical Solutions to Problems in Experimental Mechanics*, 1940-1985, Vantage Press (1987), recalls using 6 g Statham accelerometers in 1950 on the first Canadian designed and built

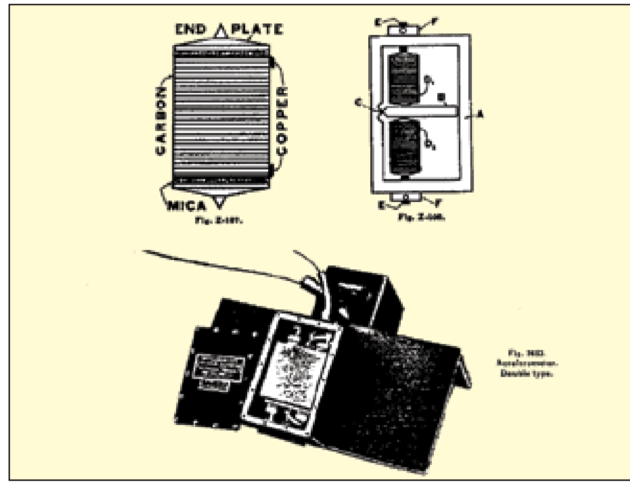

Figure 1. McCollum-Peters accelerometer based on carbon stack (1936).

helicopter, the SGVI. Referring to the accelerometer provided by Mr. Louis Statham of Statham Laboratories: "every time I used it I sent him $5.00." In 1955, C. C. Perry and H. R. Lissner authored one of the first complete texts on strain gages entitled *The Strain Gage Primer*, McGraw-Hill. This book describes Statham unbonded strain gage accelerometers "with ranges as high as ±500 g and natural frequencies as high as 4,500 cps."

The problem with all of the metal strain gage accelerometers was that they provided full scale signal outputs of approximately 30 mV. Thus, depending on the application, signal to noise ratios could be a problem. Even to achieve these signal levels, seismic systems using high compliance (low stiffness) flexures were required. These flexures resulted in low resonant frequencies and mechanically fragile accelerometers. To increase their frequency response, and at the same time decrease their fragility, accelerometers were often fluid damped to 0.707 of critical. This damping would increase their useable frequency response by a factor of three while decreasing the amplification at their resonant frequency to approximately 50% of their zero frequency value. However, the penalty assessed by the introduction of this fluid damping was to make the frequency response of the accelerometer highly temperature dependent when operated more than ±20 or 30° F from room ambient conditions.

The frequency constraints associated with these early strain gage accelerometers limited their application in measuring high frequency vibration and therefore short duration shocks. David E. Weiss reports in a 1947 paper[2] on testing of Naval aircraft structures at the Naval Air Experimental Station (NAES), Philadelphia: "accelerometers are required for the following types of tests: pullouts and other flight maneuvers; normal and arrested landings; and catapult launchings." Mr. Weiss describes accelerometers developed at NAES patterned after units built at Douglas Aircraft Company. Also described are Statham units with ranges from ±12 g to ±40 g and natural frequencies ranging from 400 to 500 Hz. Weight of the Statham 12 g unit was "approximately 2 oz." Mr. Weiss' paper models the response of an accelerometer to both a step function and triangular pulse for various damping values and concludes that "While much more mathematical analysis remains to be done in determining the response of accelerometers to pulses, it is evident that high natural frequencies are required to record transients." At the same conference where Mr. Weiss presented this paper, Mr. W. P. Welch, Westinghouse Research Laboratories, presented a second paper[3] on a proposed new shock measuring instrument. This paper abstract starts: "No very suitable instrument now exists for the measurement of mechanical shock from field tests. This includes measurements made on ships, airplanes and other vehicles." Mr. Welch used a Westinghouse Transient Analyzer to study accelerometer transient response to four types of simple shock motion. This increasing emphasis on shock measurement encouraged Levy and Kroll, in 1951, to perform an analytical study[4] at the National Bureau of Standards concerning accelerometer response to transient accelerations. This study investigated accelerometer response to half-sine, triangular, and square pulses. The controlled accelerometer parameters were damping ratio and ratio of accelerometer natural period to pulse duration. This work was also funded by the Navy through the Bureau of Aeronautics.

Piezoelectric Sensors

The solution to the transient response problems identified in the above described studies of Mssrs. Weiss, Welch, and Levy and Kroll came as a result of the introduction of the piezoelectric accelerometer into the transducer market place. The piezoelectric materials used had high moduli. In addition, their self-generating responses produced wide dynamic signal ranges. Both of these properties combined to enable the design of accelerometers with high resonant frequencies. These high resonant frequencies eliminated the need for damping to extend the accelerometer's useable flat frequency response. Phase shift over the useable frequency range of the accelerometer also was eliminated. This large dynamic signal range also allowed size reduction of piezoelectric accelerometers relative to strain gage accelerometers while providing much higher g capability. As proof of the improved properties of piezoelectric accelerometers for vibration measurements, one can assess National Bureau of Standards reports 6907 and 70665,[6] which surveyed the performance of representative piezoelectric and bonded and unbonded strain gage accelerometers manufactured sometime prior to 1960. None of the strain gage accelerometers had flat frequency response above 200 Hz while the piezoelectric accelerometers provided flat response to 10,000 Hz. As Statham Instruments and other transducer companies owe their existence to the development of the strain gage, a plethora of accelerometer manufacturers owe their existence to the integration of piezoelectric technology into transducers.

The late 1940s and early 1950s were an exciting time as numerous manufacturers of piezoelectric accelerometers came into existence. The piezoelectric materials used included ferroelectric and nonferroelectric (e.g. quartz). The early ferroelectric ceramics used were primarily barium titanate. Piezoelectric transducers, which are basically ac coupled high-pass circuits at low frequencies, originally utilized cathode follower vacuum tube signal conditioning. Charge amplifiers were next developed and subsequently a two-wire integrated (FET) circuit was incorporated into the accelerometer itself. The charge amplifier eliminated the voltage dividing effect of the cable capacitance bothersome to the cathode follower circuit. The placement of integrated circuit technology within the accelerometer, which is today's principal technology, eliminated much of the triboelectric-based cable noise bothersome to the charge circuit. Accelerometers with integrated circuits are typically sealed units capable of operating over long lines in various harsh environments.

The status of accelerometer development in 1953 is summarized in reference 14. This reference describes a May 14-15, 1953 Symposium on barium titanate accelerometers. Over 250 people attended this symposium focused on the increasing importance of shock and vibration measurements to military requirements. Four half-day sessions dealt with: (1) the properties of barium titanate (a relatively new piezoelectric ceramic material), methods of polarization, dependence of charge sensitivity with crystal size, material stability, material and piezoelectric constants; (2) the design factors and performance tests of barium titanate accelerometer construction, calibration, frequency response, linearity, temperature and pressure effects and cable noise; and (3) the instrumentation associated with the accelerometers. A Naval Research Lab accelerometer Type C-4 one in. high and weighing 5 oz was reported on as operating to 7000 g. A NBS Type OBI-14 accelerometer weighing 7.4 gms with a 90 kHz resonance was described! Gulton had a large array of accelerometers: Models A-312, A-314, A-320, A-403, A-413, A-410 and A-500. Weights from 2.5 to 52 gms were reported with resonant frequencies to 35 kHz.

The principal early corporate pioneers and their first locations included Brüel & Kjær (Denmark), Columbia Research Laboratories (Woodlyn, PA), Endevco (Pasadena, CA), Gulton Manufacturing (Metuchen, NJ), and Kistler Instruments (Buffalo, NY). It is interesting to note that all of these companies are still in existence today. Columbia Research Laboratories and Gulton Manufacturing (now Gulton-Statham) have become broad-based transducer houses so that piezoelectric accelerometer development is no longer their central focus. Brüel & Kjær is currently focused as a systems house, transducers being one part, with about half of its product line directed towards shock and vibration. Kistler Instruments has split since its initial founding with the portion maintaining the Kistler name having a broad piezoelectric accelerometer line and a historical focus on force and pressure measurement. The significant company emerging from Kistler was PCB Piezotronics. PCB is a rapidly growing company with an increasing focus on piezoelectric accelerometers, particularly in the modal and industrial areas. Endevco has maintained a consistent focus on shock and vibration measurements and, in addition to a piezoelectric accelerometer line, has evolved an extensive silicon micromachined accelerometer line. Wilcoxon Research, although not founded until 1960 and a "job shop" facility for many years, is mentioned because of its early ties to the David Taylor Model Basin and its pioneering work in mechanical impedance heads. A brief history of all of these companies and some of their accomplishments follow. The amount of coverage provided to each is dependent on the duration of their corporate existence, the history they contain in accelerometer development for shock and vibration, and the amount of their product focus on shock and vibration measurements over the years. It is in no manner judgmental on the companies or their products.

Figure 2. B&K Model 4303 accelerometer – probable first commercial piezoelectric accelerometer (~1945-1948).

Brüel & Kjær

Brüel & Kjær (B&K) is located in Nærum, Denmark, specializing in sound and vibration measurement instrumentation. B&K began in 1942 in a small town north of Copenhagen, Denmark. Per V. Brüel and Viggo Kjær, recent university graduates, started a product line with an electronic voltmeter which expanded to now include over 200 instruments and transducers.

B&K designed its first piezoelectric accelerometers in 1943 made from Rochelle salt (water soluble) crystals mounted as square bender plates with a corner or one side free and sometimes loaded with clamped weights. Their sensitivities were 35-50 mV/g and their resonant frequencies were 2-3 kHz. The B&K Model 4303 shown in Figure 2 probably represents the first commercial piezoelectric accelerometer. Ceramic elements replaced the Rochelle salt crystals in the early 1950s. As a result, accelerometer sensitivity was approximately doubled and the resonance increased to 5 kHz.

Compression type accelerometers were introduced into B&K's product line in the late 1950s with design modifications in 1964 resulting in a new series with reduced susceptibility to case-loading and base-strain. From 1968 to 1975 further improvements were made in the compression design. In 1958, B&Ks U. S. presence increased with the opening of their Cleveland, OH facility.

Their first shear m odeaccelerometer (Type 8307) evolved in 1972. Their DeltaShear® design emerged in 1974 consisting of three masses and piezoelectric elements arranged around a triangular center post to further minimize base-strain and thermal coupling. This design was further standardized for interchangability (UniGain®) and subsequently (in the1990s) incorporated integrated circuits (DeltaTron®). ThetaShear® accelerometers are currently a low cost version of this integrated-circuit accelerometer for volume applications. B&K's 100,000 g accelerometer model is the 8309. Their transducer development for sound and vibration continues with an increased focus on complete systems. B&K probably currently provides the most turnkey system of manufacturers discussed. They also maintain a focus on accelerometer calibration systems. B&K remained a family run business until 1992 when the company was purchased by AGIV, a German based company.

Columbia Research Laboratories

Columbia Research Laboratories was founded in 1955 by Victor F. Alibert and his sister Olive as a part time operation to build high temperature strain gages developed at the Philadelphia Naval Shipyard. In 1959 their brother Dr. Vernon F. Alibert joined the business and applied his background in physics and environmental testing to develop a product line of ferroelectric ceramic shock and vibration accelerometers. Columbia's facility has remained in Woodlyn, PA throughout its existence. Dr. Alibert left the company in 1981. In 1964 Columbia won a major contract for vibration monitoring on the Apollo program. Representative piezoelectric products have included those for the USAF's ICBM program, fuse applications for Picatinny Arsenal, differential piezoelectric accelerometers/charge amplifiers for nuclear power plant operations, and airborne vibration measurements using hybrid assemblies. Their current catalog includes shock accelerometers (e.g. Model 5004) to 100,000 g and piezoelectric accelerometers using both charge mode and integrated electronics technology. Their main focus today, however, is on applying numerous types of sensor technologies to the industrial marketplace.

Gulton Manufacturing

Gulton Manufacturing was founded in the early 1940s in Metuchen, NJ by Dr. Leslie K. Gulton as a chemical company. In 1946, Glenn Howatt joined Gulton from the MIT Laboratory, having patented the formulation of sheet barium titanate as the first man-made replacement for natural piezoelectric crystals. Glenco Corp. was set up after Mr. Howatt's arrival and ultimately became part of Gulton Industries. Barium titanate was first applied to sonar applications and Abe Dranetz, who arrived at Gulton in 1948, along with Mr. Howatt, made the first practical commercial piezoelectric vibration accelerometers in the U. S. in 1949. Prior to that time, Brush Instruments (which became Clevite) had made only a crude ADP-based piezoelectric accelerometer which weighed about three oz. Clevite chose, however, to focus primarily on piezoelectric material development and never became a significant accelerometer manufacturer.

In the late 1950s Gulton was principally making compression and bender-type accelerometers from ferroelectric ceramics under the trade name of Glennite (named after Mr. Howatt). The bender design possessed less spurious effects due to base strain and acoustic coupling into the accelerometer than did the compression design. In low-g ranges, this bender design was fluid damped and was the only piezoelectric accelerometer to accomplish this.

In 1964, Gulton bought Electra-Scientific (founded 1960) in Fullerton, CA, primarily to attain rights to their bolted shear piezoelectric accelerometer design. They consolidated all their piezoelectric operations in Fullerton in 1965. The bolted shear design addressed the base strain sensitivity issue and allowed stacking of elements for temperature compensation.

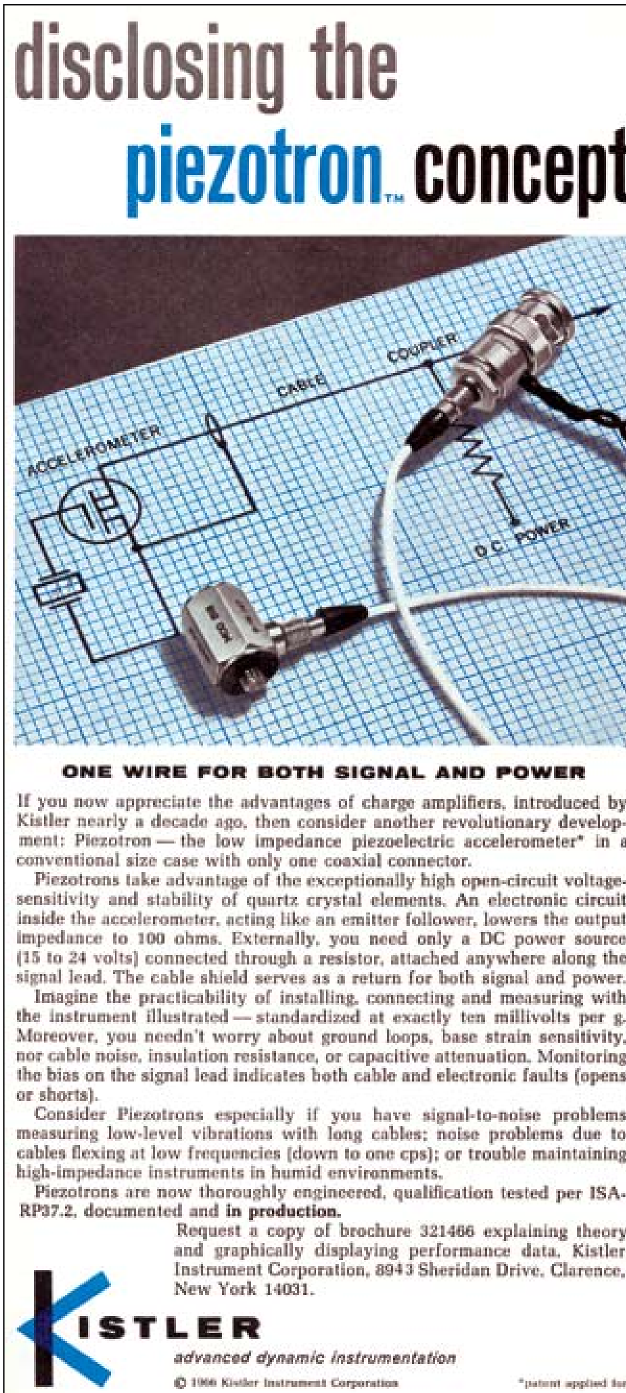

Figure 3. Kistler Model 818 accelerometer – probable first commercial accelerometer with 2-wire integrated FET (circa 1965).

In the mid 1960s Gulton developed a proprietary piezoceramic (G-1900) enabling manufacture of the AQB 4901 accelerometer (patent awarded 1969) and then others for engine vibration monitoring to 1000° F. In 1967 they consolidated with their Servonics Division, a general purpose transducer capability, to become Gulton Servonics in Costa Mesa, CA. Mark IV industries acquired them (1986) and the remainder of Louis Statham's original company (1992), to form Gulton-Statham. Gulton-Statham produces charge and integrated circuit (w/gain since 1980s) accelerometers today with a decreased emphasis on shock and vibration. Their current focus is on various types of transducers for broad based applications.

Kistler Instrument Company

Kistler Instrument Company began operations in America in 1954 and was incorporated in January 1957. Mr. Walter P. Kistler started to develop piezoelectric measuring instruments in 1944 while at the Swiss Locomotive and Machine Works. In the early

1950s, as an engineer at Bell Aerosystems in Buffalo, NY, Mr. Kistler marketed the Swiss Locomotive and Machine Works transducers in the U. S.

After performing further product development and leaving Bell, in 1962, Kistler built a facility in Clarence, NY. Kistler Instruments was next acquired by Sundstrand Corporation in 1968 and moved to Redmond, WA in 1970. Subsequently, they were acquired by Kistler Instrumente AG, Switzerland (which had been a Swiss counterpart since 1958) in 1979 and moved to Amherst, NY (present location). Kistler's consistent focus has been on quartz transducers, principally for force and pressure measurements. Mr. Kistler was granted a Swiss patent for a charge amplifier June 16, 1950, and Kistler Instruments received a U.S. patent in 1960.

Kistler's first quartz accelerometer and vibration calibration standards were patented in 1962. Kistler originated the concept of incorporating a two wire integrated circuit (a FET) within a piezoelectric accelerometer. This was in the 1963-1965 time frame with the trademark PIEZOTRON® filed July 8, 1968. Figure 3 shows the Model 818, the first Kistler PIEZOTRON in a two wire version. This is likely the first commercial two-wire FET based accelerometer.

Quartz is an extremely linear piezoelectric material with a reasonably high temperature capability. Quartz accelerometers tend not to zero shift as do some of the soft ferroelectric ceramics due to small changes in their remnant polarization vector due to shock loading.[7] Since quartz has a smaller compressive piezoelectric constant and less capacitance than most ferroelectric ceramics, the early quartz accelerometers used preloaded crystal stacks, mechanically in series and electrically in parallel. Under severe shock loading, the crystals might inadvertently experience relative motion within the stacks and produce zero-shifts for reasons not associated with the piezoelectric properties of quartz. The compression mode design was also susceptible to base-strain effects similar to compression designs of other manufacturers. Kistler's 805A was the first (about 1966) 100,000 g quartz accelerometer introduced to the market and its 805B (about 1970) was the first 100,000 g single crystal quartz accelerometer. At present, the U. S. portion of Kistler's operations principally manufactures numerous accelerometer types including quartz shear. The combined Kistler operation has approximately 450 employees.

PCB Piezotronics

PCB split from Kistler in 1967 as an independent U. S. company founded by R. W. (Bob) Lally and Jim Lally and is now larger (300 employees) than the U. S. portion of its parent. Bob Lally's history with Kistler dates back to its original 1950s founding and much of the technology that Bob was involved with at Kistler moved with him to PCB.

PCB is the company most responsible for common acceptance of integrated circuit piezoelectric (ICP®) technology in piezoelectric transducers and today is the world's largest manufacturer of this technology. PCB first placed ICP technology in a 100,000 g shock accelerometer in 1971. PCB's early focus was, as Kistler's, on force and pressure transducers. Their ICP technology moved them into the industrial accelerometer market (e. g. machinery health monitoring) with associated large quantity applications. The first PCB industrial grade ICP accelerometer (Model 308A04) was developed in 1973. The large volume industrial market created a subsequent demand for low-cost accelerometers and PCB's automatic manufacturing capability is addressing that challenge.

Experimental modal analysis evolved from the University of Cincinnati's Structural Dynamics Research Laboratory (UC-SDRL) as a technique to extract modal parameters (vibratory mode shapes, resonant frequencies and damping) from structural systems to enhance the modeling process. In 1972, PCB worked with the University to develop a "Modally Tuned" impulse hammer with integral force transducer to provide structural system excitation. This Impulse Hammer design brought PCB lasting fame and a 1983 IR-100 award. Figure 4 shows such a modally tuned impulse hammer.

Capitalizing on this entry into the rapidly emerging experimental modal analysis technology, PCB developed a Structcel Modal

Figure 4. PCB Modally Tuned Impulse Hammer of type responsible for IR-100 award.

Array Sensing System addressing sensor installation, orientation, cabling, signal conditioning and end-to-end calibration in 1983. Its 1984 Data Harvester focused on accommodating large numbers of accelerometer channels. Modal testing can routinely involve 100s of accelerometers. To encourage modal testing, PCB developed easily implemented system dynamic calibration techniques. Its Model 963A Gravimetric Calibrator (1973) enabled single channel amplitude and phase calibration. Its Model 9090C Accelerometer Array Calibrator (1986) enabled up to 128 modal accelerometers to be calibrated simultaneously for amplitude and phase based on rigid body mechanics. PCB moved into structured shear quartz accelerometers in 1986 and now works with many other piezoelectric accelerometer crystal types including the ferroelectric ones. PCB is marked today by continued rapid growth and an increasing focus on accelerometer design.

Endevco

Endevco was formed in 1947 by H. Dudley Wright, an instrument manufacturer's representative, in Pasadena, CA, and moved to San Juan Capistrano, CA in 1974. Endevco manufactured its first accelerometer in 1951. Endevco presently has divisions in several countries and is operated by Meggitt Aerospace. Mr. Wright retired as president in 1964. Endevco is one of the oldest piezoelectric accelerometer manufacturers, is currently the largest U. S. manufacturer with 400 employees and is the only piezoelectric accelerometer developer that has maintained a consistent product focus on shock and vibration. Since Endevco is unique in manufacturing both piezoelectric and silicon based accelerometers for shock and vibration, as well as its own piezoelements, its study provides somewhat of a comprehensive history in accelerometer development.

Endevco's principal accelerometer technology areas have been microminiature, high shock, high temperature and calibration development (discussed below). They developed their first charge amplifier in 1959. Their first 100,000 g piezoelectric (PE) accelerometer was marketed in 1965. The first attempt at developing a piezoresistive (PR) accelerometer for the shock and vibration measurement community occurred in 1962 using a patented butterfly bulk semiconductor gage. In 1961, a Solid State Laboratory to support PR accelerometer development was set up and now resides in Sunnyvale, CA. By 1966 a 10,000 g PR shock accelerometer was in the marketplace.

The first line-diffused semiconductor gages were developed in 1967 enabling the radiation hardened 2266 series of accelerometers to evolve in ranges to 20,000 g by 1968. An analogous configuration to the 2266 in a non-radiation hardened version was developed about this same time in ranges to 50,000 g. In April 1974 studies were performed for a 100,000 g sculptured silicon accelerometer with a free gage design. The resultant product (7270A, weight = 1.5 gm, see Figure 5A) was marketed in 1983 in ranges to 200,000 g with a 1.2 MHz resonant frequency. These PR accelerometer accomplishments were all firsts.

Returning to PE accelerometer development, an annular shear series of accelerometers was developed with patent application filed in 1959. This led to the evolution of their microminiature product line (e.g. a 0.14 gm PE with 10,000 Hz frequency response was developed in 1972, a 0.85 gm three axis version marketed in

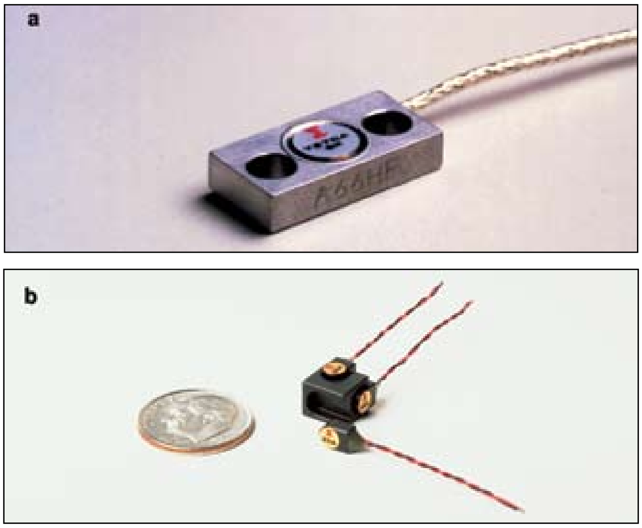

Figure 5. Endevco current accelerometer technology: (a) Model 7270A sculptured silicon shock accelerometer; (b) Model 25A 3-axis configuration microminiature accelerometer with integral electronics (1996).

1973, and 0.2 gm low impedance integral electronics single axis version marketed in 1984). Figure 5B shows a microminiature triaxial accelerometer with integral electronics providing some insight into the state-of-the-art of accelerometer technology as it exists today A 1.3 gm, 100,000 g PE accelerometer with a 250,000 Hz resonance was developed in 1969. The 7255B continued the evolution of high shock PE products in 1988 with the incorporation of integrated circuit technology and a built-in mechanical filter for pyroshock measurements. A 2270 back-to-back 'piggyback' calibration standard was developed in 1965. These accomplishments again represent firsts.

Endevco entered the high temperature market with a 750° F quartz accelerometer in 1961. Subsequently, an accelerometer (2273) with this same 750° F temperature specification but with a ferroelectric bismuth titanate sensor was released. In 1969, testing was performed on two different PE accelerometer models for aircraft engine monitoring at temperatures of 900° F and 1200° F. The 6237M70 was released with a temperature capability of 1200° F in 1981. A model 6240 tourmaline based accelerometer, in development in the early 1980s, was released as the 6240 in 1988 with an operating specification of 1400° F.

Wilcoxon Research

The final company discussed, Wilcoxon Research Incorporated, was formed by Ken Wilcoxon, Al Sykes, and Fred Schloss in 1960. Fred Schloss was an acoustical noise physicist at David Taylor Model Basin (DTMB) since the early 1950s. Mr. Schloss invented the self-driven Mechanical Impedance Head. This Head was developed to support studies of noise damping characteristics of vibration isolation mounts for shipboard machinery. The Head required a piezoelectric force transducer and accelerometer and a controllable vibration generator. The Head was patented October 13, 1959 (#3,070,996). DTMB originally built the heads and transferred them to other Navy customers.

The requirement for studies supported by the Head was intensified by the U.S. nuclear submarine program. The Navy subsequently approved a technology transfer of the Head to Wilcoxon. Soon after its forming, Mr. Sykes sold his shares in Wilcoxon Research to Mr. Wilcoxon and Mr. Schloss did the same in 1979. In 1979 the company was also transferred to Mr. Wilcoxon's sons. Today the company includes 120 employees. It primarily works in the industrial accelerometer marketplace using lessons learned from making instrumentation 'sailorproof.'. The company is located in Gaithersburg, MD.

Calibration Activities

While accelerometer development occurred primarily in private industry, calibration capabilities developed for shock and vibration evolved in government facilities, Endevco, and B&K. The National Bureau of Standards (NBS), now The National Institute of Standards and Technology (NIST), became involved in accelerometer calibration in the early 1950s. In 1956 Samuel Levy applied the reciprocity theory to accelerometer calibration and Ray Bouche did the experimental work to redesign existing electrodynamic shakers. This resulted in a vibration calibration service (started 1956) at NBS from 10-2000 Hz. Endevco's interest in calibration was focused by the hiring of Dr. Bouche from NBS. In the early 1960s, Ted Dimoff developed the NBS air-bearing shakers extending the range of electrodynamic shakers to 10-10,000 Hz with improved calibration accuracy. These are in use today and the reciprocity method is used for shaker calibration.

In the early 1950s, Seymour Edelman at NBS developed optical tools to measure the motion of piezoelectric shakers, first from 100 to 10,000 Hz, and later to 20,000 Hz. This interferometric method measures dynamic motion based on the wavelength of light. In the 1950s and 1960s the light source was a mercury vapor lamp which was replaced in the 1970s with a helium-neon laser. The laser interferometer was also applied to low frequency, from 1 to 200 Hz, calibrations in the early 1970s.

Today, all accelerometer manufacturers offer NIST-traceable calibrations. Endevco manufactured a Ling-Endevco calibration system about 1970 with a 10 lb force shaker. This shaker was followed by the Bouche shaker, developed by Dr. Ray Bouche at Endevco, which uses the Dimoff air bearing and guides a beryllium armature. This latter shaker is incorporated in the Vibracon/Bouche calibration system. Endevco's Automated Accelerometer Calibration System (AACS) was marketed in the early 1990s to support vibration calibration and subsequently shock calibration. This system also incorporates the Bouche shaker. B&K has also maintained a consistent focus on vibration calibration. Their 9610 system replaced (late 1980s) their old 9559 system. All of these are comparison calibration systems to 5-10 kHz and resonant survey systems to 50 kHz. B&K's Type 9636 is the only commercial primary system using laser light as an absolute reference to 5 kHz.

A significant challenge has always existed in the area of shock accelerometer calibration where NBS/NIST has devoted less effort than in vibration calibration. A shock calibration service was in place at NBS in the late 1960s or early 1970s and was discontinued in 1976. In 1974, a NBS publication[15] describes comparison calibration on a hydraulic pull down shock machine, using an FFT algorithm, to 1,500 g at 0.7 msec. By 1987, a shock calibration service was again operating at NBS, modeled on the technique in the 1974 report, to levels of 5,000 g at 0.3 msec. Continuing upgrades, including the addition of a ball-drop shock generator, resulted in the expansion of the NIST capability to 10,000 g at 0.1 msec by 1995. This capability is currently advertised as a "Special Test" at NIST.

Because user needs ran ahead of NBS/NIST capability, both other government agencies and private industry evolved shock accelerometer evaluation/calibration hardware. Ray Bouche developed the Drop Ball Calibrator[8] at Endevco in 1960 with a maximum capability of 15,000 g and 50 µsec duration. Photocells provided a velocity reference. Butler, Dove, and Duggin[9] developed a small bore gas gun at Sandia National Laboratories in the 1964-1965 time frame which generated pulses to 100,000 g with 100 µsecduration. An array of photodiodes provided a velocity reference. A 'Zatter' was developed[10] at Sandia National Laboratories in the 1963-1966 time frame using electromagnetic energy to propel a small aluminum projectile. A Kistler 912 load cell provided a force-to-acceleration reference. Calibration pulses were attainable to 100,000 g and 200 µsec duration. Bell[11], as part of his development of the Model 2291 accelerometer at Endevco, designed in 1969 a large exponential bar which could easily generate 100,000 g pulse trains. Sill[12] at Endevco commercialized a Hopkinson bar calibration technique in 1984. Bateman, Brown, and Davie[16] at Sandia National Laboratories applied a laser vibrometer to a Hopkinson bar as a calibration reference standard to 70,000 g and claimed ±5% resultant accuracy.

Since its inception, the accelerometer marketplace has greatly expanded. Newer manufacturer entries include Analog Devices (airbag accelerometer), Dytran (PCB spin-off), EG&G IC Sensors, Entran Devices (Kulite spin-off), Kulite Semiconductor (early

Figure 6. Accelerometer history session participants at the 67th Shock and Vibration Symposium, November 1996 – Monterey, CA. Left to Right: Mr. Len Maier, General Manager Piezoelectrics, Endevco Corporation; Dr. Raymond Bouche, former National Bureau of Standards/Endevco Corporation, current Technical Director, Vibracon/Bouche Labs; Mr. John Kubler, Vice President, Kistler Instrument Corporation; Mr. Abe Dranetz, former Vice President of Engineering and Transducer Instrumentation, Gulton Industries, retired President, Dranetz Technologies, Inc.; Mr. Robert Whittier, General Manager Silicon Sensor Group, Endevco Corporation; Mr. Walter Kistler, former President, Kistler Instruments, Inc., numerous other company starts, current cofounder, Kistler Aerospace Corporation; Dr. Patrick Walter, retired manager, Sandia National Laboratories, current Senior Design Lecturer Engineering, Texas Christian University and Senior Technologist-Dynamic Instrumentation,Endevco Corporation (session organizer); Mr. Peter Stein, former Professor, Arizona State University, President, Stein Engineering Services, Inc.; Mr. Torben Licht, numerous management positions, Brüel and Kjær; Mr. Bev Payne, Physicist, National Institute of Standards and Technology; and Mr. James Lally: President, PCB Piezotronics, Inc. (note: Dr. Walter (author) remains at TCU and has been Measurement Specialist, PCB Piezotronics, Inc. since 2003).

1970s diffused silicon beam accelerometer), and Vibra-Metrics. This expansion is continuing today.

Acknowledgments/Comments

This article contains some additional information, but only minor corrections, to the paper I included in "50 Years of Shock and Vibration Technology," Shock and Vibration Information Analysis Center (SAVIAC), Arlington, VA (1996). Since writing this paper, at the request of SAVIAC, I organized and chaired a session on Accelerometer History for the 67th Shock and Vibration Symposium, Monterey, CA, November 1996. The proceedings of this session, in SAVIAC's: *The Shock and Vibration Bulletin* – Part II, includes detailed histories by the pioneers in this industry and the presidents and CEOs of today's thriving companies.

The generous gathering and sharing of information by the following individuals, along with my own archives and recollections, made this paper possible: Bob Brown/Torben Licht (B&K), John Kubler/Mike Murphy/Spence Wende (Kistler), Bob Clark /Len Maier/Bob Whittier (Endevco), Jim Lally (PCB), John Hayer (Kulite Semiconductor/former Gulton), Bev Payne (NIST), H. Edwin Roberts (Columbia), Elmer Hazleton (Gulton-Statham), and Peter Stein (Stein Engineering). The documented stories brought to the 67th Shock and Vibration Symposium by The Pioneers (Ray Bouche (former National Bureau of Standards and Endevco), Abe Dranetz (former Gulton), Peter Stein (Stein Engineering), and Walter Kistler (former Kistler Instruments)) will serve as invaluable references for future generations. Fred Schloss, one of the Wilcoxon founders and former David Taylor Model Basin, also added significantly to the history included in this paper. As a young engineer, I had an older colleague once describe to me the results of early testing on the sled track at Holloman AFB, NM. He stated: "You never knew if you were looking at vibration signals coming from the strain gage accelerometers or vibration of the filaments in the vacuum tube signal conditioners!" We've advanced a long way in accelerometer technology since that time. The technology explosion in microsensors and microelectronics indicates we've just begun our journey.

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Epilogue

Just as the decade beginning in the late 1960s was noted as the era when analog electronics moved into the piezoelectric accelerometer, the decade beginning in the late 1990s will be noted as the era when digital electronics achieved this same distinction. IEEE standard set 1451[20] was cooperatively developed and completed by industry and the NIST. The intent of this standard was to make it easier for transducer manufacturers to develop smart devices and to interface those devices to networks, systems, and instruments by incorporating existing and emerging sensor and networking technologies. The key feature of these standards has been the definition of Transducer Electronic Data Sheets (TEDS). The TEDS is a memory device integral with the transducer, which stores transducer identification, calibration, correction data, measurement range, manufacture-related information, etc. The ultimate goal when developing IEEE standard set 1451 was to allow the access of transducer data through a common set of interfaces whether the transducers are connected to systems or networks via a wired or wireless means.

While the transmission of high frequency (many kHz) acceleration data emanating from numerous accelerometers with internal digitizers in serial networks still remains only a vision, TEDS does currently exist. Akin to the incorporation of the 2-wire analog integrated circuit within piezoelectric accelerometers 40 years ago, TEDS occupies minimal volume and is also located within conventional accelerometer housings. Among other things, TEDS automates system setup, eliminates cable connection errors, improves sensor data management and bookkeeping and contains helpful user info (e.g. sensor location). Thus, its utilization will steadily grow. Virtually every manufacturer of piezoelectric accelerometers for routine thermal operating environments (<150° C) can and do supply accelerometers with TEDS circuits.

A significant change in accelerometer technology over the past decade has been the rapid advances in silicon technology. As a byproduct, there has been increased utilization of both piezoresistive and variable capacitance silicon-based accelerometers. Later, much more will be said about the future of this technology, where it will more correctly be referred to as Micro-Electro-Mechanical-Systems or MEMS technology.

Now, let's return to the status of the corporate pioneering companies featured in the original article written in 1996. These companies all still exist. However, typical of corporate life today, many have been bought and sold by parent organizations. The companies are described in the order in which they appeared in the original article.

Brüel & Kjær (B&K) continues as a systems house, with a focus on their Pulse analyzer. After the earlier mentioned AGIV purchase, AGIV formed a group of four companies and created the new name Spectris AG. In July 2000, the UK based Fairey Group plc acquired the Spectris businesses including Brüel & Kjær. The Fairey Group changed its name to Spectris plc in May 2001. Among current accelerometer manufacturers, B&K has been especially active in integrating finite element analysis into the accelerometer design and application process. They have also developed a one-mass tri-axial accelerometer design – OrthoShear. Like other manufacturers, they have integrated Transducer Electronic Data Sheets (TEDS) into numerous designs. They have retained their focus on accelerometer calibration, and have incorporated advanced FFT analyzer techniques into this process.

Columbia Research Labs, Inc. still remains a small, privately owned company. Their recent work has been focused towards servo or closed-loop accelerometers, and they have not significantly leveraged their position as one of the early manufacturers of piezoelectric accelerometers.

Endevco Corporation, a Meggitt group company, will celebrate its 60th anniversary in 2007. Its continuing focus remains on small, piezoelectric accelerometers, but there is an increased focus on the incorporation of integral electronics into these accelerometers. Their Isotron® integral electronic models (e.g., 65HT-10) operate at temperatures as high as 175° C. In the area of silicon technology (MEMS), special models of Endevco's 7290A were thermally compensated in CY2002 to achieve limited short term navigational grade performance. MEMS continue as a focus area within Endevco, with 12 patents issued during the past ten years. Endevco's reliable Picochip accelerometer continues to be used in heart pacemakers, with over 4 million units supplied to date.

In the late 1990s, Endevco's monitoring business was transferred to Vibro-Meter, Inc. Vibro-Meter is within the same Meggitt group. Corporate efficiencies have somewhat reduced Endevco staff size. However, within Meggitt, the acquisition of Wilcoxon Research in 2004 has largely offset this size reduction.

Gulton had merged with Statham to become Gulton-Statham prior to the 1996 history being written. On April 30, 1999, AMETEC bought Gulton-Statham, primarily for their pressure transducer business.

Kistler USA still resides in NY state with headquarters in Switzerland. Kistler has added MEMS technology to their accelerometer line. These ServoK-Beam® accelerometers provide static response, high performance, and high sensitivities. Kistler recently accomplished a significant technical breakthrough when they developed their Piezostar® accelerometer line. Piezostar® affords typical thermal sensitivity shifts of less than 0.002%/° F over aerospace temperature operating ranges (e.g., –65 to +250° F). During this period, Kistler has also focused their efforts on developing a line of K-Shear® Quartz Shock accelerometers directed towards minimizing transverse sensitivity, zero shift and non-linearity.

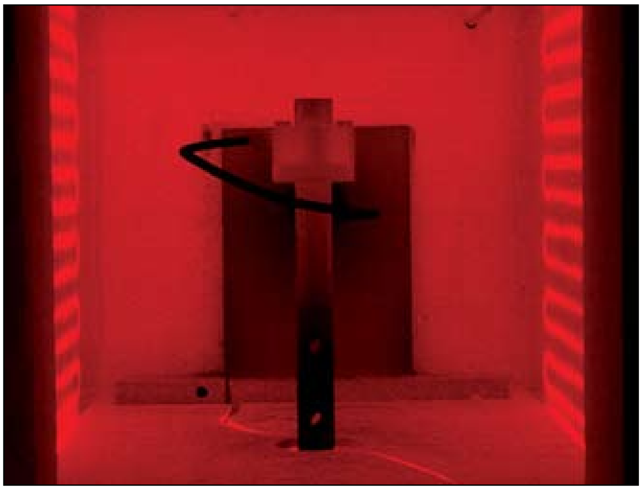

Figure 7. PCB Accelerometer Operating at 1200° F.

PCB Piezotronics, Inc., in my opinion, is the company that has achieved the most significant growth over the past ten years. Partially through acquisitions, but largely through internal growth, its total number of employees has more than doubled to between 600 and 700. It has become the largest U. S. accelerometer manufacturer. The "PCB Group" of sensor companies was formed to include: The Modal Shop, Larson Davis, Oceana Sensors Technologies, and STI Technologies. In addition, the PCB Advanced Sensor Design Center was established in Southern California, focusing on high temperature (e. g., engine monitoring) and MEMS technologies. Finally, a 50,000 sq ft manufacturing facility for stock products was established in North Carolina

In order to increase the vertical integration of its U.S. manufacturing operations, PCB now: (1) manufactures all of its piezoceramic accelerometer materials with operational capabilities to 900° F. (accelerometers under development operate to 1200 ° F as shown in Figure 7); (2) slices and cuts its own quartz; (3) has established its own connector manufacturing capability including glass to metal seals for hermetic sealing and high insulation resistance; and (4) greatly increased its calibration capabilities (The Modal Shop has achieved rapid acceptance of its accelerometer calibration stations PCB/TMS 9155C that can include air bearing shaker systems, pneumatic shock calibrators and transverse sensitivity testers). PCB's Industrial Monitoring Instrumentation (IMI) Sensors Division continues to grow and has developed an extensive product line of heavy duty accelerometers with built-in 4 to 20 mA transmitters to support low cost, continuous vibration monitoring of industrial machinery.

Wilcoxon Research is in the process of relocating its headquarters to Germantown, MD. Its principal focus remains the vibration condition monitoring market. To support this market, 4-20 mA outputs are provided along with intrinsically safe accelerometer models, cables, mounting hardware and signal conditioning.

Three other accelerometer manufacturers not mentioned among the corporate pioneers are noted. First, **Dytran Instruments, Inc.**, Chatsworth, CA, mentioned in the *Prologue*, is in its 27th year of operation, and has recently experienced 75% internal growth to 100 employees. Second, **Measurement Specialties, Inc.** (MSI), a low-cost sensor house has grown by a factor of ten in the past 10 years. MSI has recently integrated a Vibration Division whose focus is that of a high-volume supplier of piezoresistive MEMS accelerometers. Their high- performance, low-g piezoresistive MEMS die (see Figure 8) is unique. Third, **VIP Sensors** – Vibration, Impact and Pressure, was founded in 2003 by Alex Karolys. Located in San Juan Capistrano, CA, they offer a line of piezoelectric and MEMS piezoresistive accelerometers as well as the supporting electronic sensor instrumentation. However, their principal focus is the smart sensor market.

An industry summary of the past ten years in accelerometer

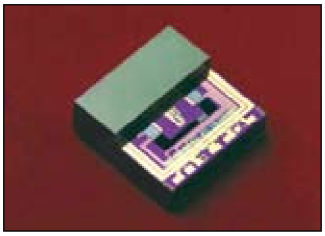

Figure 8. MSI MEMS silicon piezorsistive accelerometer die.

manufacturing would conclude that there is a leaner workplace, increased price competition, an increased focus on MEMS technology, and the integration of digital technology. In this highly competitive environment, some manufacturers are second-sourcing their products from one another as well as building products in China. More rapid changes are yet to come as accelerometers become more of a commodity.

The accelerometer was originally developed to support the test and evaluation (T&E) community. This group, with their aerospace and military specifications and budgets, drove the market for 50-60 years. Principally due to advances in analyzers, a machinery condition monitoring market has evolved over the past 25 years. The use of conditional monitoring allows machinery maintenance to be scheduled, or other actions taken, to avoid the consequences of failure. Monitoring applications encompassing large plants has forced accelerometer cost containment to become a critical issue.

As the automotive crash test industry has evolved over the past 30 years, their preference has been for MEMS accelerometers, principally because of the low frequency response they provide. The industry has been willing to pay prices for accelerometers that are similar to those of the T&E market. However, the need for an airbag accelerometer crash sensor generated a requirement within the automotive industry for a low-cost, highly-reliable accelerometer. All necessary signal conditioning and self-test circuitry had to be on the same chip with the accelerometer.

Analog Devices' manufactured the MEMS ADXL50 accelerometer, introduced in 1991 and in volume production by 1993, as the first commercially available, high-volume manufactured accelerometer to employ surface micromachining. Its size was 5 mm square. Today, in quantities of over 1000, airbag type accelerometers, made by various manufacturers, range in price from \$3 to \$12 each. The T&E market's technical requirements remain the same, but where airbag accelerometers can suffice, low cost alternatives are sometimes available.

The next opportunity for massive quantities (millions) of accelerometer sales will be in consumer electronics and mobile applications. Gaming and pedometers are but two examples. Analog Devices is successfully evolving MEMS gyroscopes. MEMS accelerometers, coupled with low cost gyros, can and will offer application in automotive stability control, rollover detection, load leveling, event recording, collision avoidance, and navigation. For consumer products, application opportunities include computer input devices, hand held navigation units, game controllers, sports equipment, camcorders, and robots. Some envisioned industrial applications are autonomous vehicles, motion control of equipment, and equipment platform stabilization. Military applications could include unmanned vehicles (land and air), antenna pointing, land navigation, and more. Biomedical applications expand this list even further. Aside from Analog Devices, other large scale MEMS accelerometer supplier names include: Bosch, Freescale, Kionix, oki Electric, STMicroelectronics, Hitachi Metals, Matsushita, Fujitsu, and Hokuriku. Again, spill-over from this consumer market will satisfy select needs in the T&E marketplace.

Thus, the future for accelerometers looks brighter than ever. However, the principal marketplace driver will not be the historic T&E market but rather the consumer MEMS market. Where MEMS technology can suffice, T&E accelerometer suppliers will not have to develop their own silicon sensing elements, but can acquire them from commercial MEMS foundries, which currently number in the dozens around the world. Accelerometers, analog signal conditioning, digitizers and even MEMS transmitters will all reside on the same substrate. In some instances, microprocessors will offer near real-time data correction. Accelerometers will permeate our lives as never before in ways we have yet to imagine. SV

The author may be reached at: p.walter@tcu.edu.