Review: Fifty years plus of accelerometer history for shock and vibration (1940–1996)

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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 today is presented.
Keywords: Accelerometer, calibration, ferroelectric, piezoelectric, piezoresistive, strain gage

1. Historical background

The earliest development of the resistance-bridge-type accelerometer, which was ultimately commercialized, is credited to McCollum and Peters [9,15]. It weighed about a pound and was 3/4 × 1-7/8 × 8-1/2″ 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 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 resonance frequency was less than 2,000 Hz. By 1936, Southwark Bulletin 132 advertised [15] 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 at 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 in 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 the inductor telemeters and slide wires".

1.1. Early commercialization of strain gage accelerometers

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 A. Ruge, Massachusetts Institute of Technology (MIT), April 3, 1938, and E. Simmons, Caltech, September 1936 [14]. 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. 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 [15]. 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 1940's when strain gage load, pressure, and acceleration transducers "made their complete and magnificent debut in flight". This was in conjunction

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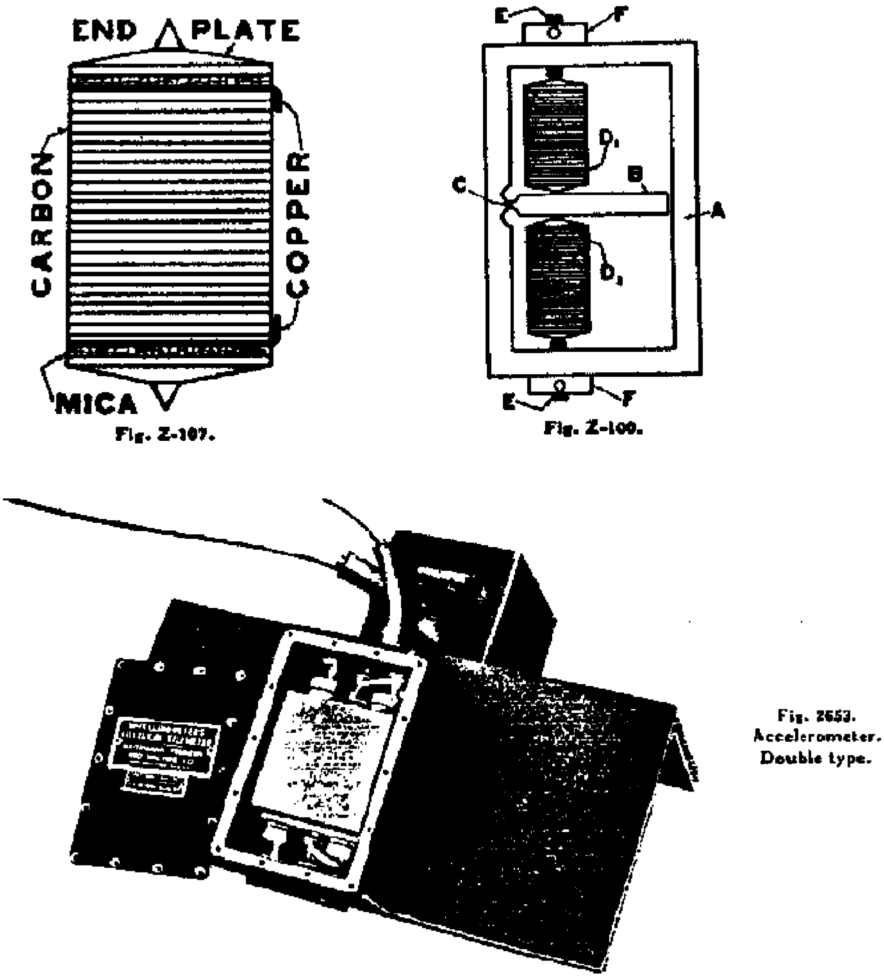

Fig. 1. The first commercial resistance-bridge accelerometer (McCollum and Peters, photo date 1936).

with cannon firing on the twin-tailed P38 aircraft and resulted in "miles of oscillograph records".

L. Statham (1907–1983) subsequently performed 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 A. 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 helicopter, the SGVI. Referring to the accelerometer provided by 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 millivolts. 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 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 percent 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. D.E. Weiss reports in a 1947 paper [16] on testing of Naval aircraft structures at the Naval Air Experimental Station (NAES), Philadelphia: “accelerometers are required for the following types of tests; pull-outs and other flight maneuvers; normal and arrested landings; catapult launchings”. 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 ounces”. Weiss’ paper models the response of an accelerometer to both a step function and triangular pulse for various damping values. It concludes “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 Weiss presented this paper, W.P. Welch, Westinghouse Research Laboratories, presented a second paper [17] on a proposed new shock-measuring instrument. This paper abstract starts: “No very suitable instrument now exists for the measurement of mechanical shock on field tests. This includes measurements made on ships, airplanes, and other vehicles”. 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 [8] 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. The Navy through the Bureau of Aeronautics also funded this work.

2. Piezoelectric accelerometer industry

The solution to the transient response problems identified in the above-described studies of Messrs. 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 7066 [6,7] 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 [11]. This reference describes a

May 14–15, 1953 Symposium on Barium Titanate Accelerometers. 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 accelerometers including 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 inch high and weighing five ounces was reported on as operating to 7000 g. An 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.

2.1. *Corporate pioneers*

The principal early corporate pioneers and their first locations included Bruel and Kjaer (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. Bruel and Kjaer 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 company or their products.

2.1.1. *Bruel and Kjaer*

Bruel and Kjaer (B&K) is located in Naerum, Denmark, specializing in sound and vibration measurements. B&K began in 1942 in a small town north of Copenhagen, Denmark. Per V. Bruel and Viggo Kjaer, recent university graduates, started a product line with a voltmeter which expanded to now include over 200 instruments and transducers.

B&K designed its first piezoelectric accelerometers in 1943 made from Rochelle salt crystals (water-soluble) 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 device shown in Fig. 2 (photo date estimated 1945–1948) probably represents the first commercial piezoelectric accelerometer. Ceramic elements replaced the Rochelle salt crystals in the early 1950's. 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&K's U.S. presence increased with the opening of their Cleveland, OH facility.

Their first shear accelerometer (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 represents

Fig. 2. The first commercial piezoelectric accelerometer (B&K, about 1943).

the most turnkey system house 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.

2.1.2. Columbia Research Laboratories

Columbia Research Laboratories was founded in 1955 by V.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 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. 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 envelops shock accelerometers (e.g., Model 5004) to 100,000 g and piezoelectric accelerometers using both charge and integrated circuit technology. Their main focus today, however, is on applying numerous types of transduction technologies to the industrial marketplace.

2.1.3. Gulton Manufacturing

L.K. Gulton founded Gulton Manufacturing in the early 1940s in Metuchen, NJ as a chemical company. In 1946, G. 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 Howatt's arrival and ultimately became part of Gulton Industries. Barium titanate was first applied to sonar applications and A. Dranetz, who arrived at Gulton in 1948, along with 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 ounces. 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 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.

In the mid 1960s Gulton developed a proprietary piezoceramic (G-1900) enabling manufacture of the AQB 4901 accelerometer (patent award 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 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.

2.1.4. Kistler Instruments

Kistler Instrument Company began operations in America in 1954 and was incorporated in January 1957. W. Kistler started to develop piezoelectric measuring instruments in 1944 while at the Swiss Locomotive and Machine Works. In the early 1950s, while an engineer at Bell Aerosystems in Buffalo, NY, Kistler selectively 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. 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 patent (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 [5]. Since quartz has a smaller compression 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 operations have approximately 450 employees.

2.1.5. PCB

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

PCB is the company most responsible for the common acceptance of integrated circuit technology (ICP®) 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 as-

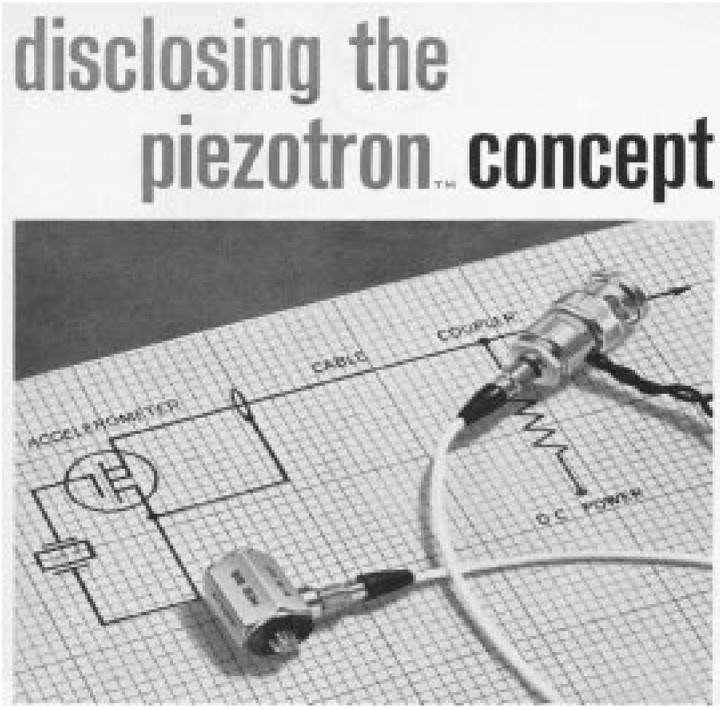

Fig. 3. The first commercial two-wire piezoelectric accelerometer with contained FET (Kistler, about 1963).

Fig. 4. The first modally tuned impulse hammer (PCB, 1972).

sociated 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 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 Array Sensing System in 1983 that addressed sensor installation, orientation, cabling, signal conditioning, and end-to-end calibration. Its 1984 Data Harvester focused on accommodating large numbers of accelerometer channels. Modal testing can routinely involve hundreds 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, and 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.

2.1.6. Endevco

Endevco was originated as a company in 1947 by H.D. 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. Wright retired as president in 1964. Endevco is one of the oldest piezoelectric accelerometer manufacturers, is currently the largest U.S. manufacturer 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 evolved 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 freed gage design. The resultant product (7270A/weight = 1.5 gm, see Fig. 5(a)) 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 1973, and 0.2 gm low impedance integral electronics single axis version marketed in 1984). Figure 5(b) 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 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.

2.1.7. Wilcoxon Research

The final company discussed, Wilcoxon Research Incorporated, was formed by K. Wilcoxon, A. Sykes, and F. Schloss in 1960. Schloss was an acoustical noise physicist at David Taylor Model Basin (DTMB) since the early 1950s. 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

Fig. 5a. The first high-g (200,000 g) sculptured silicon accelerometer (Endevco, 1983).

Fig. 5b. The smallest triaxial piezoelectric accelerometer with integral electronics (Endevco, about 1985).

transfer of the head to Wilcoxon. Soon after its forming, Sykes sold his shares in Wilcoxon Research to Wilcoxon and Schloss did the same in 1979. In 1979 the company was also transferred to Wilcoxon's sons. Today the company is located in Gaithersburg, MD. It primarily works in the industrial accelerometer marketplace using lessons learned in making instrumentation "sailorproof".

3. Accelerometer calibration capability development

While accelerometer development occurred primarily in private industry, calibration capabilities development 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, S. Levy applied the reciprocity theory to accelerometer calibration and R. 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. The hiring of Bouche from NBS focused Endevco's interest in calibration. In the early 1960s, T. 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 S. 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 calibrations, from 1 to 200 Hz, in the early 1970s.

Today, all accelerometer manufacturers offer NIST traceable calibrations. Endevco manufactured a Ling-Endevco calibration system about 1970 with a ten pound force shaker. The Bouche shaker, developed by R. Bouche at Endevco, which uses the Dimoff air bearing and guides a beryllium armature, followed this shaker. 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. A 1974 NBS publication [12] describes comparison calibration on a hydraulic pull down shock machine, using a FFT algorithm, to 1,500 g at 0.7 ms. 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 ms. 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 ms 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. Bouche developed the Drop Ball Calibrator [3] at Endevco in 1960 with a maximum g capability of 15,000 with 50 μs duration. Photocells provided a velocity reference. Butler, Dove, and Duggin [4] 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 μs duration. 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 [2], as part of his development of the Model 2291 accelerometer at Endevco, designed in 1969 a large exponential bar that could easily generate 100,000 g pulse trains. Sill [13] at Endevco commercialized a Hopkinson bar calibration technique in 1984. Bateman, Brown, and Davie [1] 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. Unreported work with laser vibrometer references has also occurred at NIST.

4. Conclusions

Since its inception, the accelerometer marketplace has greatly expanded. In addition to the aforementioned pioneers, newer manufacturer entries include Analog Devices (airbag accelerometer), Dytran (PCB spin-off), EG&G IC Sensors, Entran Devices (Kulite spin-off), Kulite Semiconductor (early 1970's diffused silicon beam accelerometer), Vibra-Metrics, and others. The current rate of technology advancement in microsensors and microelectronics indicates that future expansion in accelerometer manufacturers and capabilities will occur at an even faster pace than in the past.

Acknowledgments

This article contains some additional information, but only minor corrections, to an article published in *50 Years of Shock and Vibration Technology*, Shock and Vibration Information Analysis Center (SAVIAC, Arlington, VA, 1966). A session on Accelerometer History for the 67th Shock and Vibration Symposium, Monterey, CA, November 1996, organized at the request of SAVIAC, also complimented this work. The proceedings of this session, in SAVIAC's: *The Shock and Vibration Bulletin-Part II*, include detailed histories by the pioneers in this industry and the presi-

dents and CEOs of today's thriving companies. The generous gathering and sharing of information by the following individuals, along with my own (P. Walter) archives and recollections, made this paper possible: B. Brown (B&K), J. Kubler/M. Murphy/S. Wende (Kistler), B. Clark/L. Maier/B. Whittier (Endevco), J. Lally (PCB), J. Hayer (Kulite Semiconductor/former Gulton), B. Payne (NIST), H.E. Roberts (Columbia), E. Hazleton (Gulton-Statham), and P. Stein (Stein Engineering). The documented stories brought to the 67th Shock and Vibration Symposium by *The Pioneers* – Bouche (former National Bureau of Standards and Endevco), Dranetz (former Gulton), Stein (Stein Engineering), and Kistler (former Kistler Instruments) – will serve as invaluable references for future generations. F. Schloss, one of the Wilcoxon founders and formerly with David Taylor Model Basin, also added significantly to the history included in this paper.

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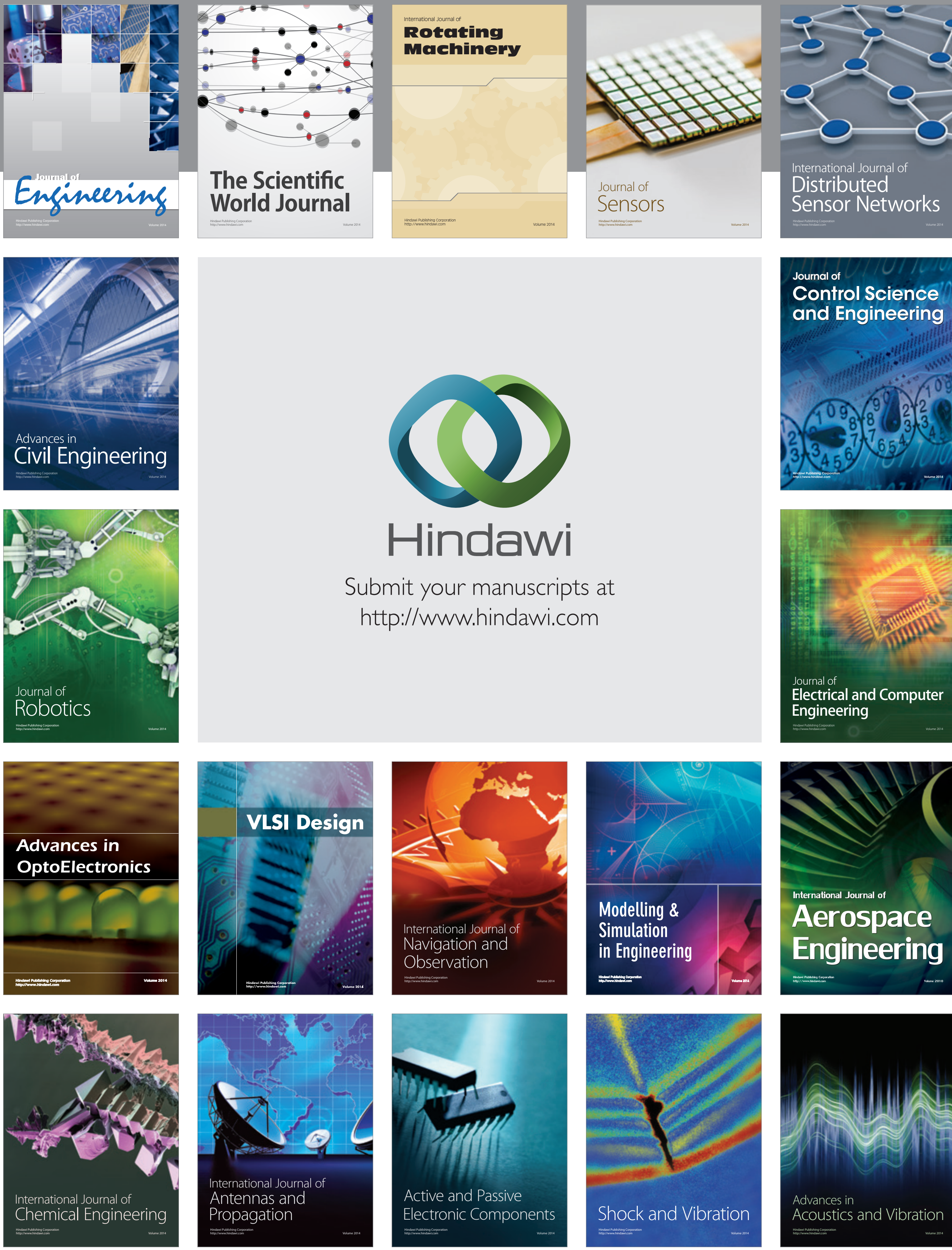
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