A HISTORY OF THE ORIGIN AND EVOLUTION OF MODAL TRANSDUCERS

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ABSTRACT

Technical advances in the past 30 years in digital signal processing, analog to digital converters, computers, and software have resulted in significant gains in the field of experimental modal analysis. Advances in transducer technology (force and acceleration transducers) have also contributed to these gains. The present work first describes the development of the early electromechanical transducers, used to measure force and acceleration, and their associated analog signal conditioning. It then focuses on the technical advances that have occurred in these transducers since the commercialization of the 2-channel digital spectrum analyzers in the beginning 1970s.

1 INTRODUCTION

In 1996, I organized and chaired the Feature Session at the Shock and Vibration Information Analysis Center's (SAVIAC's) 67th Shock and Vibration (S&V) Symposium at Monterey, CA. The focus of this session was to provide the history of the development of the accelerometer for shock and vibration measurements. I also contributed an individual paper on this topic. Since I have been involved with shock and vibration testing for over 35 years, performing these tasks was a labor of love. It was also a study in perseverance. I struggled to separate the "facts" from the "best recollections" of a number of contributing individuals who recounted, either first- or second-hand, a history that spanned more than 50 years. Even though 5 years have now passed, that effort greatly enabled this paper to be written. It is important that young engineers and technicians entering the field of experimental modal analysis appreciate and understand the history and technology associated with modal transducers. Today, when it is so easy to acquire signals and digitize them to high resolution, it is more important than ever to acknowledge that these signals are only as good as the quality of the analog signal emanating from the measuring transducer.

The 67th S&V Symposium Feature Session focused on the history of accelerometer development for numerous applications: high-shock, high-temperature, vibration testing, flight applications, and more. The current work "filters" the previous to focus primarily on modal transducers. Modal transducers encompass piezoelectric accelerometers, piezoresistive accelerometers, variable-capacitance accelerometers, force-balance accelerometers, various types of force transducers, and in recent years optical scanning techniques. However, 95% of experimental modal analysis data today originate from the signals of piezoelectric accelerometers and force transducers. Thus, these types of transducers are the focus of this paper. References 1-14 are provided at the culmination of this work. Reference 15 is more current and expands on reference 8. These in turn contain some 89 additional references. As noted previously, much of the information in this paper is extracted from them. Additional references will be specifically included at appropriate locations in the text. The advances in modal transducers since the 67th S&V (1996) papers were written are principally summarized elsewhere in two topical sessions on "Smart Transducers" that I organized for this conference (IMAC XX).

2 BODY

2.1 The Beginning Transducers

Burton McCollum and Orville Peters designed the first commercial accelerometer for which documentation could be found. It was comprised of an E-shaped frame containing carbon discs. When exposed to acceleration, the top section of the E would go into compression and the bottom section would go into tension. These sections were arranged in a Wheatstone half-bridge configuration. A paper documenting its performance and applications was written in 1923. It was used in Germany and commercialized in the United States in 1927 by Southwark, later Baldwin-Southwark, and now BLH Electronics. Resonant frequencies ranged between 250 Hz and 2,000 Hz. Figure 1 shows this carbon-stack accelerometer.

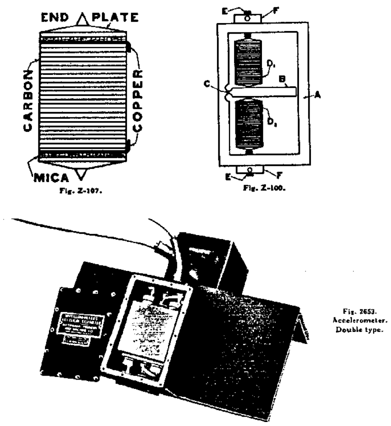

Figure 1: McCollum Peters Carbon-Stack Accelerometer As Manufactured

In 1942, Per V. Bruel and Viggo Kjaer formed Bruel and Kjaer. The company originally designed analyzers and generators for the audio frequency range. In 1943 the company branched into vibration transducers and in that year their first Model 4301 accelerometer was sold. Figure 2 is a photo of what that model likely looked like. This was the first commercial piezoelectric accelerometer. The piezoelectric material was Rochelle salt grown from dissolved chemicals. Rochelle salt had many shortcomings as a transduction material. Among those were that it couldn't operate at temperatures above 120-130 degrees F, and humidity also degraded its performance. Calibration of this first model was based on the 1G-chatter test of a vibrated metal ball.

Figure 2. Configuration of First Manufactured Accelerometer (B&K)

About this same time, Walter Kistler started his career as a instrument designer at the Swiss Locomotive Works (SLW) in Winterthur, Switzerland. The year was 1943. His initial focus was to develop a quartz pressure transducer. Seven years later, this accomplishment was complete. In March 31, 1950, he was also awarded a Swiss patent for the invention of the charge amplifier. The following year, he moved to the U. S. We will pick up his story again later.

After World War II, Glenn Howatt joined Dr. Leslie Gulton's firm - Gulton Manufacturing Company. His purpose was to develop and manufacture capacitors using titanates of barium and strontium. Howatt soon observed the piezoelectric effect in barium titanate. In 1949, a consulting German scientist (Dr. Guttwein) suggested the need for a lightweight accelerometer to support aircraft and missile vibration testing. Abraham I. Dranetz designed the first piezoelectric accelerometer in the U. S. in 1950. It was a compression-type design, had a 10 KHz resonant frequency, and weighed 1 ounce.

In 1947, Endevco originated as a company founded by Dudley H. Wright, an instrument manufacturer's representative. Endevco manufactured its first piezoelectric accelerometer in 1951. As with Gulton, the piezoelectric material was barium titanate. The units were dubbed the "kitchen" development as they were constructed in the kitchen of the wife of a mutual part-time employee of the Jet Propulsion Laboratory and Endevco.

In 1955 Victor F. Alibert and his sister Olive founded Columbia Research Laboratories in Woodlyn, PA, as a part-time operation to build high-temperature strain gages. In 1959, their brother Dr. Vernon F. Alibert joined the business and started a product line of shock and vibration transducers.

Returning to Walter Kistler's story, in 1954 he and Mr. Walter Tanner, both Swiss engineers working at Bell Aerosystems in Buffalo, NY, formed Kistler Instrument Company. Shortly after this, Bob Lally joined the company, followed by his younger brother Jim. Walter Kistler, Bob and Jim Lally, and Bill Waytena then incorporated Kistler Instruments in 1957. Concurrently, Mr. Tanner phased out of the company.

During the 1960s, Kistler expanded its product line from pressure into acceleration and force. The quartz force transducers that were developed during this period serve as the basis for the majority of our modern-day modal hammers. By 1970, Kistler had become part of Sundstrand and moved to Redmond, WA. This acquisition by Sunstrand touched off a wave of expansion in the transducer business.

Not wanting to be part of this move, in 1967, Bob and Jim Lally left Kistler and formed PCB Piezotronics. A Kistler engineer by the name of Nick Change, who started with Kistler in 1959, also stayed with the Lally's. In 1980, Mr. Change subsequently split off of PCB to form Dytran in his basement in Buffalo. Dytran is now located in Chatsworth, CA.

Interestingly enough, one of the companies that technically could be considered the earliest entrant to the modal analysis business is Wilcoxon Research Incorporated. Mechanical impedance testing conceptually bears some similarity to experimental modal analysis. This testing developed largely in the late 1950s and early 1960s. Ken

Wilcoxon, Al Sykes, and Fred Schloss formed Wilcoxon in 1960. Schloss invented the self-driven Mechanical Impedance Head while he was employed at David Taylor Model Basin. The head was patented October 13, 1959 (#3,070,996). It was comprised of a controllable vibration generator and a piezoelectric accelerometer and force transducer. Mechanical impedance testing probably hit its peak in the 1960-1970 time frame, but force-controlled vibration testing is still embraced today.

Through the early 1970s, the forerunners of modal transducers continued to become more sophisticated. Kistler and PCB continued to evolve quartz force transducers. Primarily Endevco, but also Columbia and Gulton, focused on miniaturizing accelerometers. Endevco's 1960 patent (#3,307,054) for a center-hole-mounted annular shear accelerometer was responsible for much of this miniaturization. See Figure 3. During this time period, lead zirconate-titanate (PZT) also gained acceptance as a standard transduction material.

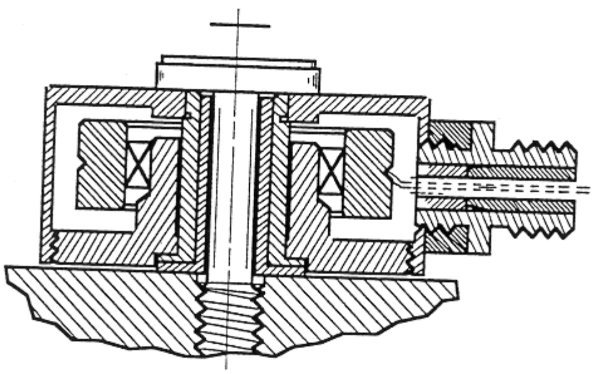

Figure 3: Endevco Center-Hole-Mount Shear Accelerometer

As accelerometers continued to evolve, the requirement for calibration standards grew. Work at the Naval Research Laboratory and at the National Bureau of Standards in 1948 enabled their calibration by absolute reciprocity to 2-percent accuracy.

2.2 The Early Electronics

The original type of signal conditioning provided to satisfy the high-output-impedance requirements of piezoelectric transducers was primarily the vacuum tube cathode follower. Gulton packaged a number of small, rugged cathode followers for flight applications in the early 1950s. During this time, a vacuum-tube signal conditioner was integrated into one of Gulton's accelerometer models. As noted earlier, Walter P. Kistler had been awarded a Swiss patent in 1950 for the invention of the charge amplifier. Development of this amplifier had begun at the Swiss Locomotive Works in 1948. The first U. S. patent for the charge amplifier was awarded to Endevco in 1959.

In 1965, Kistler instrument Corporation produced the very first piezoelectric accelerometer containing an integrated circuit. The first commercial circuits consisted of a 41004 p-channel enhanced MOSFET, a 2N3128 output transistor, and a small high-megohm resistor connected between the gate and drain to establish the input time-constant. These circuits could be hermetically sealed in a transducer with minimal size impact. The patent for this device was filed for on July 8, 1968. Kistler matured this technology further; however, its wide spread acceptance was largely concurrent with the promulgation of experimental modal analysis.

2.3 The 1970s

In 1965, the University of Cincinnati accepted a contract from the U. S. Air Force to study the structural dynamics of machine tools[16]. As a byproduct of this contract, two small companies were formed: Structural Dynamics Research Corporation (acquisition pending to EDS, August 2001) and Zonic Corporation (sold to IOTech, July 2001). After the USAF contract, the University of Cincinnati Structural Dynamics Research Laboratory (UC-SDRL) continued related vibration research.

In 1965[17], Bill Krammer (sic), a graduate student at UC, performed impact testing to support research with his professor Jack Lemmon. Structural dynamics testing in this era was dependent on analog signal recording and processing. Thus it was of great interest when David L. Brown and Ray Zimmerman (graduate student) at UC began to perform FFT-based analysis of structural dynamic signals. By 1969, Brown was calculating frequency response functions (FRFs) from dual-channel impact response data. About this same time, a relationship between UC and Hewlett Packard (HP) was established.

In the early 1970s, Prof. Brown, Ken Ramsey, Hank Fallick, and Skip Ross formed a company to build and sell modal impact hammers. In the 1971-1972 frame, Prof. Brown met Bob Lally at an SAE show, and Bob proposed that PCB build these hammers. As a byproduct of this meeting, PCB entered the modal hammer business.

Experience gained during the use of these hammers over the next 10 years indicated that the structural input signals they produced introduced glitches in the resultant computed FRFs. To solve this problem, in the early 1980s, Richard Lally evolved this hammer further by modally tuning it to locate its vibratory nodes at its head, thus eliminating the effects of its structural resonances (Figure 4). This resulted in an IR100 award for PCB in 1983. Additional modal hammer versions followed (e.g., electric). Kistler and Dytran also developed quartz-based modal hammers, but their entry into this market was later than PCB's.

Figure 4: PCB IR Award Modal Test Hammer

The ongoing relationship that PCB established with UC-SDRL enabled them to become firmly entrenched as the principal supplier of transducers to the modal test community. It also enabled the ICP® power supply trademark for their integral electronic piezoelectric transducers to become associated with HP's frequency analyzers and subsequently those of other manufacturers. Other PCB innovations followed (e.g., Data Harvester®, Structcel®, etc.). Most of this development was focused on reducing cost and/or increasing the efficiency with which large-channel modal tests could be performed.

In 1981, Endevco released their first integral electronic piezoelectric design. Until this happened, they weren't in a position to give serious consideration to the modal market. At this time both Endevco and B&K independently manufactured ceramic accelerometers, while Kistler and PCB independently focused on quartz. Each technology was almost a badge of pride to its respective proponents.

It has to be recalled that the initial focus for Kistler, the parent of quartz technology, was pressure and force measurements. The ability of quartz to operate linearly to extremely high stress levels is a significant advantage for these measurements. When integrated into accelerometers, however, the lower sensitivity of quartz versus the ferroelectric ceramic piezoelectric materials is a disadvantage. Figure 5 shows a cut-away of a 1960s Kistler accelerometer. Note that to achieve a high sensitivity, the crystals are stacked mechanically in series and interconnected electrically in parallel. They operate in a compression mode.

Figure 5: 1960s Type Kistler Quartz Stack Compression Mode Accelerometer
(courtesy Lawrence Livermore National Labs)

When designing modal transducers, it is desired to minimize their mass to avoid loading the parent test structure to which they are affixed. As quartz accelerometers were designed progressively smaller, the number of crystals they contained had to be reduced, which lowered their sensitivity. In addition, as they became smaller, the error contribution due to the base-strain sensitivity of the single-crystal, compression designs became undesirably large. Thus it's interesting today that the original manufacturers of quartz transducers now have a significant product line of ceramic accelerometers. Conversely, many of the original manufacturers of ceramic accelerometers now have a product line that includes quartz modal hammers.

Today PCB still dominates the modal transducer market. The most recent challenge to this position was initiated in 1999 when B&K and Endevco formed an alliance. The byproduct of this alliance was to combine Endevco's accelerometer manufacturing capabilities with B&K's system capabilities to provide more focus in the modal area than either could provide individually.

Independent of this challenge, as we look to the future, the company that is most successful in developing the technologies and gaining the customer acceptance for both smart and wireless transducers will dominate the modal market. These emerging technologies are featured in other sessions of this conference.

3 CONCLUSION

This work has attempted to provide a history of the evolution of modal transducers. At this juncture, the only certainty is that advances in modal transducers, encouraged by the rapid advances occurring in electronics and telecommunications, will occur at an ever-accelerating rate. Demand for their use will be driven by their increased versatility, lower costs, and the emerging technology of smart structures.

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