As We Enter the Second Century of Electroacoustics…

Stephen C. Thompson

Address:
Graduate Program in Acoustics
The Pennsylvania State University
Room 201, Applied Science Building
University Park, Pennsylvania 16802
USA

Email:
sct12@psu.edu

A look back at a century of electroacoustic transducers and systems and an attempt to look forward.

Introduction

The term *electroacoustics* is generally understood to include the design, development, and use of devices that convert acoustical signals to electrical signals, and vice versa. To some, the term may be limited to the field of audio engineering, where it describes the use of microphones, loudspeakers, and audio recording and production techniques. This article, however, takes a broader view to include devices working in media other than air such as sonar systems, underwater acoustic communication, and medical ultrasound systems. It does not include biological systems, such as the human ear, that convert sound into electrical nerve impulses or electrical discharge systems such as lightening that produces thunder. It also limits the discussion to transducer and acoustic system design and does not include the more artistic endeavor of audio recording and production.

I believe that the modern subject of electroacoustics requires the existence of electronic amplifiers to preserve at least reasonable signal fidelity. With this requirement, modern electroacoustics began with the introduction of vacuum tube electronics that could provide high-impedance preamplifiers and reasonably linear low-impedance driving amplifiers for the output devices. Vacuum tubes were invented in the first decade of the twentieth century (Fleming, 1905; De Forest, 1907), although it took another couple of decades until they achieved the aforementioned characteristics. With this definition, the history of modern electroacoustics began about a century ago. However, there was a significant prehistory of less capable devices that were ready for the improvements possible when electronic amplifiers became available.

The telegraph of the mid-1800s may actually be considered a primitive electroacoustic device. The telegrapher's key acts as a switch at the transmitting end to send pulses of electrical current through the circuit. At the receiving end, the current pulses pass through a coil. These current pulses magnetically actuate a mechanical device whose motion generates clicking sounds. Although this system is primarily electromechanical in operation, it is the clicking sound at the receiving end that conveys information via Morse code to the receiving operator. Thus, the telegraph may be considered an electroacoustic system, although that is a huge stretch of the modern understanding of electroacoustics.

There was an early audio recording industry before the advent of electronics. That industry and its methods and devices were covered previously in *Acoustics Today* by Brock-Nannestad (2016). The early telephone system was also developed without electronic amplifiers in the late nineteenth century. The telephone circuit was an electrical direct current loop that included a carbon microphone and a moving armature speaker in the earpiece.

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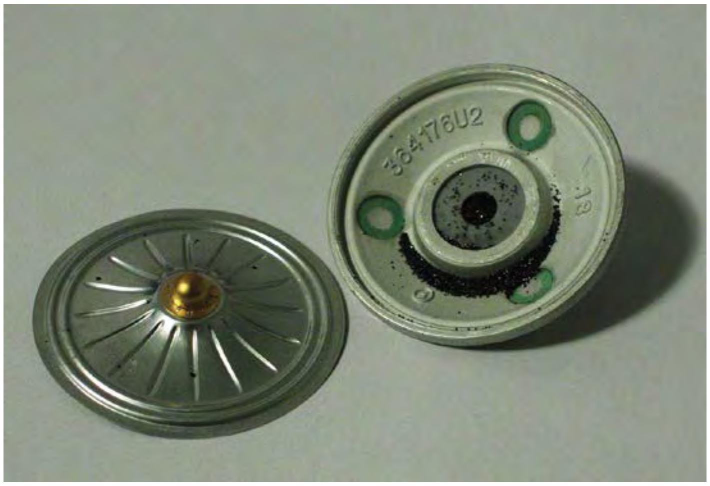

Figure 1. *An open carbon microphone capsule showing the internal carbon granules (**middle right**) and the flexible pressure diaphragm (**left**). The post at the center of the diaphragm transfers the acoustic pressure to the carbon granules. From bit.ly/2Ul6lrK*

The carbon microphone is simply an enclosed capsule containing loosely packed carbon granules (e.g., **Figure 1**). This capsule is often called a "button," and the carbon microphone is often called the carbon button microphone or just the button microphone in the literature. The carbon granules are somewhat electrically conductive, and their package has a flexible membrane that allows acoustic pressure to cyclically compress the thickness and compact the carbon particles so that the electrical resistance across the package varies with the pressure signal.

The early telephone system operated without the active amplification we understand today. The circuit did, however, have a constant voltage source that created a nominal circuit current. The resistance of the transmission line was constant, so the varying resistance of the microphone caused a signal current variation to be imposed on the otherwise constant current from the voltage source. At the receiving end of the transmission line, the varying current passed through a coil in a magnetic earphone. The audio signal from the microphone end was reproduced in the earphone with reasonable loudness and clarity. The sensitivity, bandwidth, internal noise level, and signal distortion would be considered poor by present listeners. But it was possible to transmit the limited bandwidth voice signal for several miles through the telephone cable. By transferring the signal through repeater circuits to successive transmission cables with separate current loops, it was possible to transmit the signal over much longer distances. The repeater included is a magnetomechanical driver similar to the earphone drivers in the telephone and another carbon microphone. This mechanical actuator in the input current loop drives the carbon microphone in the output current loop. The constant voltage source in each current loop provides the power to enable the gain in signal amplitude across the repeater.

Considerable progress was made beyond the carbon microphone and the magnetic earphone. By 1925, most of the currently known major transducer types operating in air had been described. This includes the dynamic microphone (Siemens, 1874), the condenser microphone (Wente, 1922), the balanced armature speaker (Egerton, 1921), and moving coil speakers (Rice and Kellogg, 1925). Transducers that could operate underwater were investigated during and after World War I (see the article by Sustick in this issue of *Acoustics Today*). Among the first hydrophones was a carbon button microphone packaged in a watertight housing with a flexible waterproof window to allow acoustic pressure to compress the carbon granules. In addition, the first piezoelectric transducers for underwater use were developed using quartz crystals. The basic transducer structures were known, but better materials and improved design methods were not yet available. **Figure 2** shows some of these early devices.

By the 1930s, vacuum tube electronic amplifiers were sufficiently available so that textbooks on acoustics described the operation of microphones and speakers in ways that assumed electronic amplification would be used. Books such as *Applied Acoustics* (Olsen and Massa, 1936) in the United States and *The New Acoustics* (McLachlan, 1936) in Great Britain described the state of practice between the two World Wars. This article takes this time period as the starting point for the first century of electroacoustics.

Developments from two different directions gave birth to the significant improvements in device and system performance during the twentieth century. The first is consistently improving methods of performance analysis and prediction of acoustic devices and systems. Methods of hand calculation in the first half of the twentieth century were replaced by computer analysis since midcentury. The second major theme is improved materials and manufacturing methods that allowed each generation of designers to see designs and performance in the last part of their careers that was unimaginable when they entered the technology area.

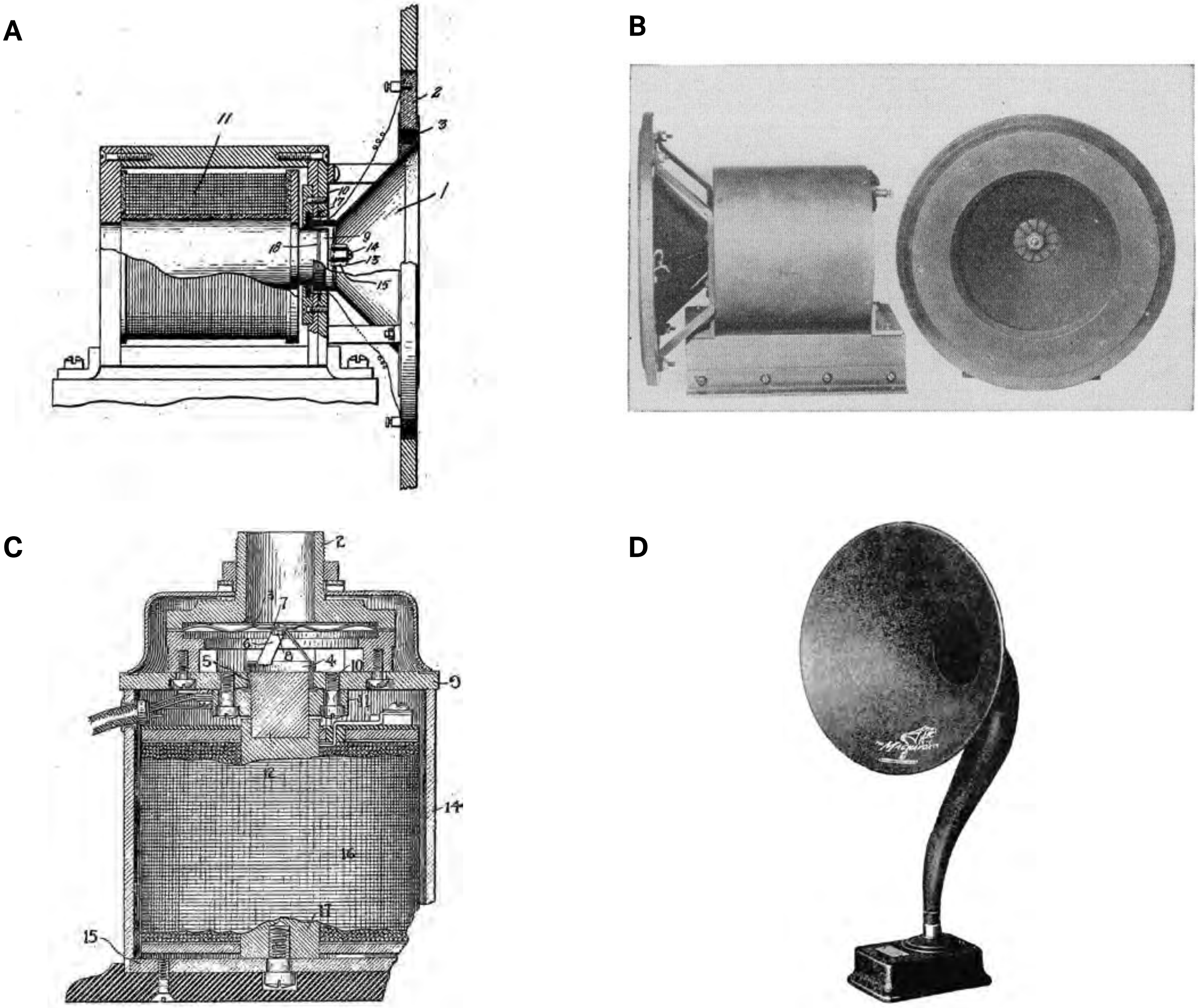

Figure 2. Examples of transducer devices that were available c. 1925. ***a:*** *Drawing showing the internal construction of an early moving coil speaker. Note the large "field coil" (****left****) that provides the static magnetic field required for actuation. From Rice, 1929.* ***b:*** *Photograph of a speaker built as shown in* ***a****.* ***c:*** *Patent drawing showing the internal construction of a horn loudspeaker driver. From Pridham and Jensen, 1923.* ***d:*** *A horn loudspeaker using the driver from Pridham and Jensen, 1923.*

Progress from the 1920s Through the 1950s

The 1920s and 1930s hosted the beginnings of electroacoustics as known it today, and the vacuum tube initiated a growing electronics industry. This was both enabled and enhanced by the start of the broadcast radio industry and by the growing audio and movie recording industries. The availability of high-input impedance preamplifiers enabled the use of both condenser microphones and dynamic microphones. These microphones have significant advantages of lower internal noise and greater available bandwidth compared with the lower cost carbon microphones that continued to be used in the telephone system. For loudspeakers, the availability of electronic power amplification enabled public address systems in auditoria and audio presentation in movie theaters.

Significant developments in material science brought the availability of strong permanent magnets using ferrite ceramics and Alnico metal alloys. (Alnico is a family of metal alloys of iron with aluminum [Al], nickel [Ni], and cobalt [Co].) Without these good magnets, earlier magnetic transducers generally needed field coils powered by direct current to generate sufficient magnetic fields. The new magnetic materials enabled the design of balanced armature and moving coil speakers without the static power dissipation of field coils.

This time period also saw the first use of ultrasound transmission for commercial applications (see the article in this issue of *Acoustics Today* by Suslick on the history of ultrasonics). Firestone was awarded a patent (1942) for the concept of "flaw detection" in solids using ultrasound. This work would grow into the field now known as nondestructive testing (NDT) that searches for flaws or imperfections in solid parts and welds in a way that does not damage or affect the performance of the parts so that they can continue to be used. The first application of medical imaging using ultrasound was in 1956 in Glasgow, Scotland. Both of these topics remain active areas of research and continued product development.

This time period also greatly expanded the development of the analysis methods considered standard today. Analog circuit models of transducer structures have multiple advantages, at least for electrical engineers, in merging seamlessly with the electrical transmission lines and filters that were part of most electroacoustic systems and with the thought process and design intuition of system designers. By midcentury, these methods were included in textbooks (e.g., Olson, 1947, 1958; Beranek, 1954; Hunt, 1954). These analysis methods, of course, preceded the development of modern computers but enabled the design and development of recording and playback devices of consistently improving quality and fidelity.

This was also a time period that saw the early development of undersea systems. World War I had seen the employment of German U-boats with devastating consequences to shipping lanes. Some of the first hydrophones in that time period employed carbon microphones in watertight housings that coupled the acoustic pressure through flexible membranes. Like telephone microphones, these early hydrophones did not have electronic amplification but could be operated with the static current from a battery. During World War II, simple devices evolved into complete active and passive sonar systems, with transducers based on magnetostriction in nickel.

By the end of the 1950s, the world of acoustic transduction had entered a state that would be mostly recognizable, if viewed as somewhat quaint, by the students of today. Everything was quite large by current sensibility, and essentially nothing could be powered by batteries. However, recognizable predecessors of the devices used today were generally available as seen in **Figure 3**. The Brüel & Kjær (B&K) series of condenser measurement microphones had just been introduced. Vacuum tube electronics had advanced considerably as broadcast television grew. Laboratory electronic equipment included the Hewlett-Packard audio oscillator and Tektronix oscilloscopes. Moving coil loudspeakers had the general appearance of more modern devices. Long-playing vinyl recordings (LPs) were no longer new, and stereophonic recordings had recently been released.

Underwater transduction also saw significant advances after the end of World War II. Activities during the war had identified the need for far greater capability in naval sonars. Piezoelectric material developments provided vast improvements in sensitivity and power handling capability for underwater transducers (Berlincourt et al., 1964). By the end of this period, the ceramic material lead zirconate titanate, usually called PZT, was taking over many applications in underwater transduction. PZT has higher performance than other the piezoelectric materials due to its relatively high electromechanical coupling coefficient. As a ceramic, it can also be manufactured in a wide range of sizes and shapes to be used in a wide variety of transducer configurations. The development of naval high-power sonar arrays was then just in its infancy, but many of the early developments quickly migrated to the use of PZT.

Perhaps the single event that had the greatest technological impact in the second half of the twentieth century was the invention of the transistor in 1947. The development of transistor electronics and the nascent use of computers for computer aided design set the stage for another wave of progress in acoustic transduction. Of course, advances in materials and materials processing also continued to be important.

Progress from the 1960s Through the 1980s

Throughout the middle of the twentieth century, telephone companies continued to use carbon microphones in their handsets because they were small, rugged, inexpensive, and good enough for the telephone system. Small condenser microphones might have provided better performance, but the need for a large external bias voltage precluded their use.

That limitation was removed when Sessler and West identified a suitable material and a manufacturing process for making an electret that could retain its charge indefinitely (see West, 1988, for a discussion of this discovery). The word electret had been used for a long time to mean a material

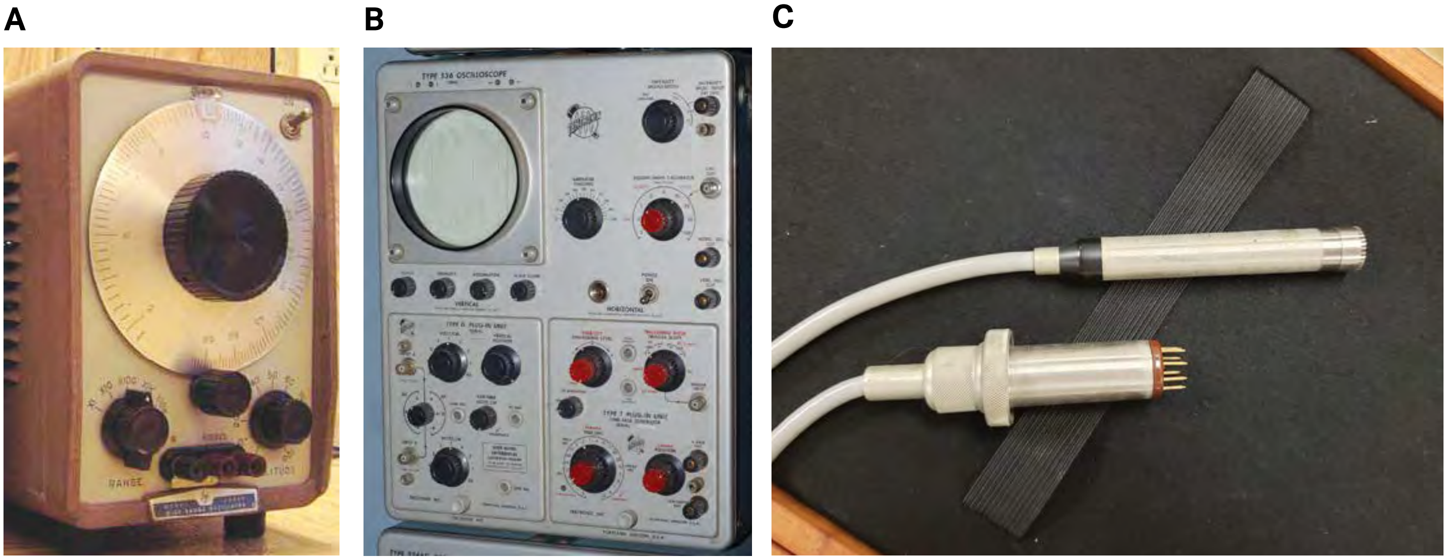

Figure 3. Much of the laboratory equipment c. 1950 is recognizable by current researchers. ***a:*** *The Hewlett-Packard 200CD audio oscillator was introduced in 1952. From bit.ly/30Kk8u3.* ***b:*** *The capabilities of this Tektronix 535 dual-beam oscilloscope would be welcome in current acoustics laboratories. From bit.ly/2Zzv1ld.* ***c:*** *The Brüel & Kjær (B&K) standard measurement microphones were introduced in 1958. Shown here is a B&K 4134 0.5-inch microphone. The cylindrical package behind the microphone diaphragm cartridge contains a cathode follower (vacuum tube) preamplifier.*

that stores a permanent electric field in an analogous way that a magnet stores a magnetic field. The potential benefits of a good electret had been hypothesized, but no good electret materials had ever been identified or produced. In fact, Gutmann (1948, p. 470) reports the use of very poor electrets in the microphones of captured Japanese radio equipment during World War II. However, the microphones in the captured equipment were nonfunctional because their electrets had discharged.

The electret developed by Sessler and West is a thin film of polymer material that permanently stores a large electric charge (West, 1988, provides an overview of that development). The electret film can be bonded inside the electrostatic gap of a condenser microphone or used as the diaphragm of that microphone. In either case, the charged electret creates a strong electric field across the electrostatic gap and eliminates the need for external electrical bias. By 1975, the electret microphone had begun to replace the carbon microphone in the telephone and other consumer equipment and also replaced magnetic and ceramic microphones in hearing aids and other miniature earpieces. Electret microphones were the obvious choice for use in cellular telephones when that market began to grow through the 1980s and 1990s.

In underwater transducer technology, the availability of PZT ceramic materials enabled a wide range of underwater transducer designs that provide the full suite of capabilities for surface ship and submarine sonars. Most of this development was not publicly documented, but enough has been reported to provide some understanding of the magnitude of the developments. For example, a retrospective article by Hueter (1972) describes some of the US Navy sonar development. Among these was the use of large cylindrical or spherical arrays including hundreds of piezoelectric transducer elements. By the end of this period, standard texts (Wilson, 1985; Stansfield, 1991) included design guidance and simple analysis methods to understand these elements and their performance in arrays of any size.

Hueter (1972) mentions some significant problems that were discovered and eventually solved in the development of the large sonar arrays. “The real problem occurred in the early 1960s with two active low-frequency arrays built for the ARTEMIS and the LORAD programs. Both arrays demonstrated local hot spots where the effective element impedance assumed negative radiation resistance values which were traced to mutual impedance terms that, until this time, had been ignored by most array designers” (Hueter, 1972, p. 1029).

The problems were acknowledged and methods to reduce the symptoms were developed (Carson, 1962). However, a full treatment of the analytical methods needed to understand these problems became available in the open literature only recently (Sherman and Butler, 2007).

Advances in ultrasonic transduction using the new piezoelectric materials enabled significant growth of field of NDT. Its use was common, for example, in inspecting the integrity of airframes, nuclear reactor cooling pipes, and the integrity of welds in the structure of pressure vessels. Continuing research and commercial development in NDT had now broadened beyond just finding cracks and flaws in a structural element. Under the name Structural Health Monitoring, it had grown to include the continuous or periodic assessment of a structure to determine the need for service, repair and eventual replacement of parts in the structure.

The use of ultrasound for medical diagnosis and treatment had also continued to grow. Biomedical acoustics had become a major industry (O'Brien, 2018).

Also, through the 1960s, the electronic computer began to take on the complicated analyses that are needed in engineering design. This was a significant aid in the design of the transducer elements, and it was essential to deal with the complexity inherent in the large arrays. Generally, the relevant computer codes did not have public distribution. One exception was the SEADUCER (Steady State Evaluation and Analysis of Transducers) code developed by the San Diego Navy Laboratory (Ding et al., 1973). This code could provide a frequency domain analysis of the electric, mechanical and acoustic performance of a piezoelectric transducer. This and contemporary competing analysis codes at other laboratories and industrial design activities were the first examples of computer-aided design specifically intended for acoustic transducers. Much of the work concerning sonar transducer element and array analysis from the last decades of the twentieth century has been preserved in a collection assembled by Benthien and Hobbs (2005).

The Last Decades of the Twentieth Century

The dual themes of increasing capability of computational resources and the development of improved materials and manufacturing methods continues. Preexisting custom computer codes for transducer and acoustic system analysis began to be replaced by more general-purpose codes whose development costs could be supported by a wide range of product technologies.

An example is the SPICE (Simulation Program with Integrated Circuit Emphasis) code for the analysis of increasingly complex integrated circuits being used for analog circuit models of multidomain systems including transducers. SPICE was originally written at the University of California, Berkeley (e.g., Nagel, 1975). Another example is finite element analysis (FEA) codes. Initially, these were written only for structural mechanical analysis. Now they were being broadened to allow and encourage multidomain analysis (Decarpigny et al., 1985).

A significant material improvement was the development of high-strength rare-earth magnets, culminating with neodymium-iron-boron magnets with significantly greater magnetomotive force capability. This, in combination with FEA magnetic field design methods, has enabled the design of significantly greater power-handling ability in moving-coil speaker designs. The improvements in speaker performance that were evident at the turn of the century have continued to the time of this publication. To those of us who purchased our first stereo systems in the 1960s or 1970s, the available output power level and sound clarity available in current commercial home entertainment systems seems remarkable.

By the end of the century, small electret microphones had become nearly ubiquitous in telephones and nearly all consumer devices. The internal noise level of small electret microphones precluded use in professional audio applications, in hearing aids, and as measurement microphones where accurate, long-term calibration is necessary. In those applications, electrically biased condenser microphones or dynamic microphones continued to be used. In fact, it was not the noise or stability of the electret that created this situation. Rather, it was the low-cost materials and electronic components and low-cost manufacturing methods that caused the noise and stability concerns. Electret measurement microphones have been introduced in the present decade.

Having invented the electret microphone that was now dominant in the market, Sessler and West, among others, went on to invent the silicon microphone as a possible replacement technology (Holm and Sessler, 1983; Lindenberger et al., 1985). This is a technology that uses the integrated-circuit manufacturing processes to build a condenser microphone structure into the silicon wafer. It was conceived as a way to integrate the mechanical structure of the microphone and the electronic components of the buffer amplifier onto the same silicon chip. The silicon microphones built during this time period had low-sensitivity and/or low-manufacturing yield that kept them from being competitive as production products. It would take about two decades from the initial concept publication for anyone to develop a viable commercial product.

Entering the Twenty-First Century

Much of the progress in the last two decades has been to consolidate the advances that were evident at the close of the last century. On the computational front, FEA codes have continued to advance and to provide enhanced multidomain analysis features and to provide significantly enhanced graphical user interfaces that make it easier for the design experts to use the codes. Several FEA codes now included the ability to simultaneously model several physical domains (e.g., mechanical, magnetic, and electric domains) and to include the relevant interdomain coupling equations.

Analyses that might previously have been done with analog circuits and SPICE are now done with greater flexibility using new analysis languages. This activity started with the development of the Modelica programming language specifically intended for modeling complex physical systems in several domains. The continued development of this language is managed by The Modelica Association, with information available at modelica.org. Commercial and freely available Modelica simulation environments are available (Modelica Association, 2019). A similar modeling environment called Simscape is available from MathWorks (2019).

Continuing improvements have already been mentioned for moving-coil speakers in performance venues and home theater applications. The performance available in many compact, battery operated Bluetooth-connected speakers is an example that may be familiar to current readers.

The audio quality delivered by smartphones has also made significant advances in the last decade. Much of the improvement likely comes from careful analysis of sound generation by the microspeakers employed and from equally careful analysis of the sound propagation through the small passages and orifices in the device. Similar developments have also been made in the design of earphones and in-ear monitors for stage musicians. Manufacturers of microspeakers have responded to new requirements by developing devices with a wider range of performance parameters to better match the demands of manufacturers of smartphones and earphones.

Another important development is the commercial availability of single-crystal piezoelectric material with a very high electromechanical coupling coefficient. Although this material development was initially funded by the Office of Naval Research for naval applications, its first broad commercial application is in medical ultrasound transducers. The primary advantages in these devices are smaller size and wider transducer bandwidth.

Biomedical applications of ultrasound have continued to expand and improve as *Acoustics Today* has occasionally reported. These improvements include the use of microbubbles to improve image contrast (Matula and Chen, 2013), therapeutic uses of acoustically driven microbubbles (Gray et al., 2019), higher resolution systems operating at higher ultrasonic frequencies (Kettering and Silverman, 2017), and the use of ultrasound to aid in the transport of therapeutic agents across the blood-brain barrier (Konofagou, 2017).

The silicon microphone was introduced as a commercial product in 2004. Current terminology places the silicon microphone in the category of microelectromechanical system (MEMS) devices. Initial sales volumes of the MEMS microphones increased rapidly as mobile phone manufacturers quickly switched their production away from electret microphones. A primary initial advantage was the ability of automated soldering methods in the production to connect the microphones to the circuit board. Those methods are used for all other components in the device, but they could not be used with electret microphones that need to be soldered in place by a manual operation because automated soldering would damage or destroy the low-cost electret microphones.

MEMS microphones are also generally smaller than other microphone types, including the miniature electret microphones that had previously been used in hearing aids and earphones. Their small size makes them suitable for use arrays because they can be made into a compact spherical array of microphones that are useful in measuring the three-dimensional nature of the sound field.

The term ambisonics has been used for this type of measurement since the mid-1970s (Fellgett, 1973). Initially, Fellgett proposed using four microphones arranged in a tetragonal

Figure 4. *The Eigenmike® spherical microphone array is the first to provide higher order ambisonic beam patterns to record the spatial characteristics of a sound field. From mh acoustics, with permission.*

array. The sensor outputs were processed to form an omnidirectional beam and the three dipole patterns along three orthogonal axes. The intent was to record these four signals and use them to reconstruct the sound field in a room using speakers positioned for the room.

Methods for reconstructing the sound field are many, but the fundamental strategy for recording has been retained. Ambisonic recording now includes not just the dipole patterns but allows for the inclusion of quadrupole patterns and higher order multipoles when they are available. In fact, higher order ambisonics has conceptually come to include all of the spherical harmonics (Tarzan et al., 2019). However, there are practical difficulties in forming the higher order beam patterns. For the *n*th order multipole patterns, the sensitivity varies as the *n*th power of frequency. Thus, for low frequencies, the sensitivity is low and the signal-to-noise ratio becomes problematic. After the initial patents (Elko et al., 2009), commercial products now exist, with spherical harmonic patterns up to fourth order (mh acoustics, 2019). **Figure 4** shows one of these products.

What Next?

It is easy to predict that evolutionary changes to the present devices and systems are likely to provide small improvements to those systems. It is also easy to say that larger changes are likely to arise from new materials, new manufacturing processes, and advances in engineering analysis. That statement has always been true. But where are those advances to be found?

I cannot claim clairvoyance in this (or any other) area. However, it is true in the past that most of the material advances that enabled major improvements in acoustical devices were not primarily motivated by the market for acoustical devices. Advances in permanent magnet materials in the 1930s presumably had much larger markets in the manufacture of electric motors and electric-power generation equipment. Neodymium magnets are used in electric vehicles and in wind turbine generators. Improvements in other magnetic materials may be possible, and cost reductions may continue as sales volumes increase. These seem likely but will probably not result in revolutionary system improvements.

One application area that may lead to changes is the improvement in analyzing and reproducing the effects of directional sound. Work in ambisonics may aid our understanding of the details of the complex wave fields that are judged to provide a superior listening experience. The requirement to provide a realistic virtual reality experience may generate new requirements for sound recording and reproduction equipment.

Improvements during the first century started slowly as vacuum tube electronics took hold. We may expect the rate of change in the next decades to be much more rapid because advances in electronics, computational capabilities, and advanced materials are all in progress.

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BioSketch

Stephen Thompson is a research professor in the Graduate Program in Acoustics at Pennsylvania State University (University Park). His PhD research was on nonlinear feedback oscillation in woodwind musical instruments. He has previously worked in industrial research and development, first for a sonar system manufacturer and later for a manufacturer of miniature OEM audio transducers. His current work includes the analysis, design, and use of acoustic transducers in a wide range of applications. He enjoys the challenges of advising acoustics students through their academic research and watching their careers develop after graduation.