Absolute Pressure Calibrations of Microphones

Historically, various techniques have been used in acoustics to attempt to establish and to measure sound pressures. At present the most accurate, precise, and convenient methods over a broad range of frequencies involve the primary calibration of laboratory standard microphones by "reciprocity techniques." The adoption of these reciprocity techniques followed many years of exacting work involving other measurement techniques and other investigators. In the paper, *Absolute Pressure Calibrations of Microphones* [1], Richard K. Cook provided both theoretical and practical understanding of these new techniques. By rigorous, systematic experimental work and analysis, he demonstrated the weaknesses of certain older, previously dominant methods. Then, by comparing results from these older methods with those of the new reciprocity techniques, he established the superiority of the latter. Reciprocity techniques were soon employed in critical inter-laboratory comparisons, which quickly led to the elevation of these techniques to their dominant status as the preferred method in primary acoustical calibrations and measurements of sound pressure.

These measurements are important because sound pressure, which is usually expressed as decibels relative to a reference pressure of 20 μPa [2], is a critical measure of acoustical signals. These signals may be speech, music, or noise. Excessive sound pressure causes hearing loss, interference with speech reception, disrupted sleep, and other annoyances. A very large and increasing number of national and international legal, regulatory, and quality control standards for health, safety, and commerce depend on measurements of sound pressure. Primary methods at national metrology institutes (NMIs) support these needs via various explicit or implicit chains of traceability. Such chains relate measurements that necessarily entail high accuracy (for example, those of major calibration laboratories and instrument manufacturers) to measurements that require lesser accuracy, such as practical laboratory and field verifications and checks supporting survey measurements for occupational hearing conservation purposes.

Cook's paper can be appreciated by considering it in the historical context of some of the many techniques that have been used to determine sound pressures in given kinds of sound fields. All techniques have relative advantages and disadvantages with regard to uncertainty, applicable ranges of frequency and amplitude, and convenience. At various times, particular techniques and apparatus became favored or dominant, and were in turn superseded by newer methods.

In the late nineteenth century Rayleigh [3] determined the threshold of human hearing by using a microscope with an eyepiece-micrometer to measure the displacement amplitude of the vibrating prongs of a tuning fork, which excited an acoustical resonator as a sound source. Later researchers in the twentieth century [4,5,6,7] sought better and more convenient sound sources of known strength, or better instruments for measuring sound fields. The thermophone used an alternating current (sometimes superposed on a larger direct current) to produce a periodic variation of temperature in a conductive wire or foil. The temperature variation in the wire or foil caused a layer of gas to expand and contract, thereby producing a calculable sound pressure. However, the method had numerous components of uncertainty that were difficult to correct for. Thermophones now are seldom, if ever, used for primary calibrations.

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Another calculable source of sound pressure is the pistonphone, in which one or more mechanically driven pistons produce a known time-varying volume displacement in a small (relative to a wavelength of sound) cavity of known volume. Practical mechanical problems have limited pistonphones to use at low frequencies, on the order of 250 Hz.

The electrostatic actuator attempts to apply a known source of equivalent sound pressure to the electrically conductive diaphragm of a microphone. This device uses an electrically conductive plate (usually slotted or perforated) to which an alternating voltage is applied relative to the microphone diaphragm. From the resulting alternating force of electrostatic origin, the equivalent sound pressure on the diaphragm is calculated. As Madella [8] recognized, the actuator-determined response of a microphone only approximates calibration in the sound pressure field (this is often called a pressure calibration). However, actuators are accurate enough to be used for secondary calibrations.

The invention of the wide-frequency-range capacitor (condenser) microphone by Wente [9] provided the next advance in instrumentation for sound pressure measurements. The sensitivity of this device could be calibrated by primary sources, and the microphone could then be used to measure sound pressure. Wente used both a pistonphone and a thermophone to calibrate the microphone [10]. He called this microphone a transmitter, a word usage still found in present-day telephone terminology, although much of the other literature uses "transmitter" to mean a microphone driven as a sound source. In the acoustics literature "response" is often used equivalently with "sensitivity." The unit of sensitivity is now expressed as the ratio of SI derived units V/Pa, but the older literature, including reference [1], uses the ratio (cm_2 volts)/dyne. The sensitivity level (response level) of a microphone is now usually expressed in decibels (dB) with respect to the reference quantity 1 V/Pa.

Research continued as systematic differences between different sources of sound pressure became evident. By 1932 Ballantine [11] described not only the theory of the pistonphone, but also the underlying mathematical physics and some experimental results for the electrostatic actuator, the thermophone, and a small moving-coil sound source for which the output plane-progressive-wave sound pressure was measured by the Rayleigh disk method (also described in [4,5] with further references).

In 1940, Cook's analysis of these systematic differences led to his introduction of what became known as the reciprocity method for the pressure calibration, or determination of pressure sensitivity, of microphones [1]. From extensive experiments, Cook observed good agreement between calibrations by reciprocity and those carried out using the electrostatic actuator, the pistonphone, and the optically measured displacement amplitude of smoke particles. However, he also observed discrepancies between calibrations using thermophone methods in air, hydrogen, and helium, as well as discrepancies between these thermophone methods and the other methods that among themselves produced consistent agreement. His theoretical and experimental work, along with the independent theoretical work of MacLean [12], clearly established the validity of the reciprocity method for calibrating microphones.

In the United States, both cooperative and independent research subsequently included Cook at the National Bureau of Standards, Wiener and DiMattia at the Cruft Laboratory at Harvard University, and Olmstead and Hawley at the AT&T Bell Laboratories at Murray Hill, New Jersey [6,13]. The development of the Western Electric (WE) 640AA microphone [6,7] provided a stable modern microphone. Although no longer manufactured, the WE 640AA microphone still satisfies the specifications [14] for an IEC type LS1Po laboratory standard microphone, and numerous samples have met the specification in reference [14] for the long-term stability of a Type LS1P standard microphone (long-term drift in sensitivity level less than 0.02 dB/year). The newer WE 640AA microphones were used in inter-laboratory comparisons of calibration results among the laboratories of NBS, Harvard, and AT&T Bell. For each of the three microphones for which results were reported in 1945 [13], calibrations among the laboratories agreed within 0.2 dB at frequencies from 50 Hz to 9 kHz, typically somewhat better at frequencies below about 5 kHz, and within 0.3 dB over the frequency range 9 kHz to 11 kHz. These results demonstrated that measurements of sound pressure over a wide frequency range using stable standard microphones calibrated by the reciprocity method were superior to the use of the best available standard sources such as the thermophone.

This demonstrated superiority eventually led to the dominance of reciprocity methods as the primary calibration methods in acoustical laboratories of NMIs around the world. Modern pressure calibrations of microphones by reciprocity techniques are more accurate, more elaborate, and may use much more complex apparatus than Cook had available, but they are fundamentally similar.

In 1982, Cook's classic paper [1] was reprinted in its entirety in the *Benchmark Papers in Acoustics* series [4]. Assessing the contributions of various researchers, H. B. Miller [4, pp. 232-233] noted the significance of accomplishments represented in Ballantine's 1929 paper [15] and stated that an extract from this paper "is so similar to Schottky's work and so foreshadowing that of MacLean, that the wonder now is that Ballantine missed being the inventor of the absolute reciprocity calibration method. . . . Moreover, in his 1932 paper (Paper 25), Ballantine omitted all reference to the method, thereby presumably implying that he felt it had no future. . . . All the greater credit, surely, belongs to Cook and to

MacLean for having the courage to challenge the great prestige of Ballantine." (Miller's "Paper 25" is our reference [11]).

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Richard K. (RK) Cook was born in Chicago and obtained his B.S. in 1931, M.S. in 1932, and Ph.D. in 1935, all in the field of physics, from the University of Illinois. In 1935 he joined the National Bureau of Standards, and he spent most of his professional career there. He served as the Chief of the Sound Section from 1942 until 1966, where he contributed extensively to the technical literature on the subjects of microphones, microphone calibration, architectural and room acoustics, reverberation room characterization, piezoelectric properties of crystalline quartz and, eventually, the field of infrasonics. During these years, he also served as Associate Editor of *Sound* (1962-3), Senior Editor of the *Journal of the Washington Academy of Sciences* (1955), and Editor of the Acoustics section of the *American Institute of Physics Handbook.* In 1966 he left NBS temporarily to become Chief of the Geoacoustics Group in the National Oceanic and Atmospheric Administration, where he concentrated his technical talents on infrasonics. He returned to NBS in 1971 as a Special Assistant on Sound Programs, reporting to the NBS Director, and served in this capacity until his official retirement in 1976. After retirement, Cook acted as a consultant to NBS on acoustical matters.

Cook also held a number of teaching posts, instructing in mathematics for the U.S. Department of Agriculture Graduate School between 1941 and 1950 and in various courses in mathematics, physics, and engineering for the NBS Graduate School and Catholic University. He acted as Adjunct Professor in the Electrical Engineering Department of Brooklyn Polytechnic Institute in 1956 while on sabbatical from NBS and carrying out research at Bell Telephone Laboratories.

He is a Fellow of the Acoustical Society of America, the Washington Academy of Sciences, the American Physical Society, and the American Association for the Advancement of Science, and he served as President of the Acoustical Society of America in 1954-1955. Cook's accomplishments span an extraordinary gamut of the subdivisions of acoustics, with respect to both physics and engineering, and they include exceptional service to technical societies, standards committees, and the body politic in general. Many people remember RK's involvement in their own particular fields, but he is truly a "Renaissance Man of Acoustics."

Prepared by Victor Nedzelnitsky.

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