QuadTech

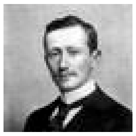
Application Note

A Bridge to the Future
Capacitance Measurements through the Ages

How did we get to the highly accurate LCR instrumentation we have today? Where did we get the technology for increased speed and precise accuracy over such a wide range of frequencies? Put aside the demands for 'more…more… more… now… now… now' and let's take a look back at the pioneers in passive component theory and test. Wander if you will through the journals of the technical brains that set the wheels in motion.


Michael Faraday

Where did the industry come from? The wheels of wireless communication and resultant test instrumentation were set in motion by a series of brilliant theorists and scientists. From James Maxwell's proof in 1864 that electrical waves could and must exist in space based upon Michael Faraday's previous experiments, to Heinrich Hertz who proved Maxwell's theories in 1890 and to Guglielmo Marconi who in 1901 transmitted the first signal across the Atlantic from England to Newfoundland. In 1906, Lee DeForest's invention of the vacuum tube drastically changed signal-receiving equipment making it no longer necessary to harness great amounts of power to transmit a signal a great distance. Also during this time inventors were working on principles of heterodyne circuits, high frequency alternators, high vacuum tubes and x-ray technology. Radio professionals and amateurs alike were now seeking variable capacitors, spark gaps, crystal detectors and other components for use in transmitters.


Gugliemo Marconi

Hence a commercial radio industry was born in the first decade of the 20th century. With this boom in electronics however came a great need for measuring instrumentation. Already in existence at this time was precise instrumentation for DC voltage, current and resistance measurements and some capable AC test equipment. But for the high frequencies necessary in radio transmission (rf is today defined as 10kHz-100GHz), there was very little measuring equipment available. Armed with this knowledge and a clear vision of the future of communications, Melville Eastham formed General Radio Company in 1915. Let's take a look at General Radio's instrumentation line from conception to present day. Just how did we get from the large analog instruments with adjustable steel knobs and dials to the sleek digitally controlled units we now have that require only the push of one button?

Analog Bridges

Bridges were big back in the 1920s, the electrical kind that is as shown at right. In 1921 General Radio introduced the 216 Capacity Bridge, the first of it's kind. Capacitance from 1uuF to 10uF could be measured at a frequency of 200 - 10,000cps. The term cps (cycles per second) was used as the unit of frequency until the late 1960's when the unit Hertz (Hz) was adopted. This ratio-arm bridge was not a stand-alone unit however and needed an external power source, null indicator, capacitance standard(s) and balancing condenser for operation. Still this instrument gave precise readings for small values of capacitance with an accuracy of approximately 0.1%.

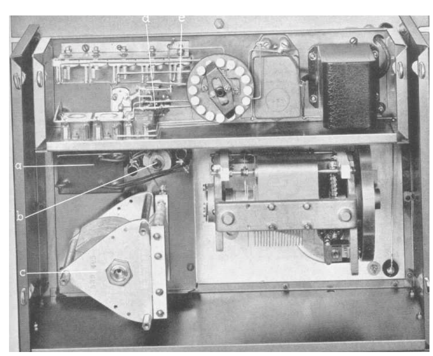
216 Capacity Bridge

The word capacity, coined by Faraday, was used to describe the charge potential between two plates until the 1930's when the term capacitance superseded it. In the 1930's measuring instrumentation was developing rapidly using vacuum tubes and quartz crystals, trying to meet the demands of radio frequency measurements.

In 1939/40, Hewlett Packard produced the HP200 Oscillator from a General Radio patent where no inductors were used, just resistors and capacitors with degenerative feedback. This design feature substantially reduced cost. In 1945 General Radio released the GR 720A Heterodyne Frequency Meter that contained a butterfly circuit consisting of a variable air capacitor. Both circuit inductance and capacitance vary up or down simultaneously without the use of sliding contacts. When used in the rf oscillator circuit, this design permitted wide variations in frequency with a single turn of the control knob.

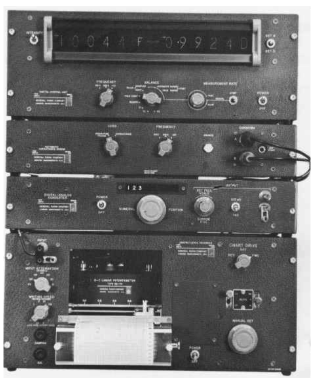
716-B Capacitance Bridge

The bridge circuitry used in the 1942 Type 716-B capacitance bridge provided two measurement methods: direct or substitution. Using the Direct method, capacitance measurements of 100uuf (100pf) to 1uF and dissipation factor measurements of 0.002% to 56% (0.00002 – 0.56) were possible. Using the Substitution method, the capacitance range was 0.1pf to (1nf with internal standard) or to 1uf with external standards. The dissipation factor (ratio of component's real resistance to imaginary reactance) was calculated as 56%(C'/C_X) where C' is the capacitance of the standard condenser and C_X is the capacitance of the unknown. Along came the bipolar transistor in 1948 developed by Shockley, Bardeen and Brattain at Bell Telephone Laboratories. It still had to be proved, but transistors would turn out to consume less power, be less costly and more reliable than the vacuum tube.



The Transformer & Printed Circuit Boards

In the 1950's television was big as was jet aircraft. Measuring the fuel gauges in jet aircraft was complicated as jet fuel is a non-homogeneous chemical compound that exhibits a broad range in dielectric constant. With jet fuel, the expansion in volume during heating is balanced by the reduction in dielectric constant. The capacitance is a measure of the height of the fuel in the tank and a self-balancing bridge should indicate an accurate fuel level. A sensing element is added to the fuel tank to introduce the appropriate correction to the bridge circuit. General Radio developed the MD-1 Field Variable Capacitance Tester to adjust and calibrate this fuel gauge technology. In 1956, Shockley, Bardeen and Brattain won the Nobel Prize for the transistor that then became commercially available and rapidly replaced the vacuum tube. Fairchild Semiconductor Corporation was formed in Palo Alto CA and Lockheed moved its operation there in 1956.



The 1960's brought great change in the electronics and instrumentation industry not to mention to society in general. Much research was being done in the field of semiconductors specifically for the space program that would revolutionize the industry a decade later but in the mean time transistors ruled the circuit world. Smaller circuit boards consisting of more reliable transistors were used in instrumentation. Dedicated 'plug-in' circuit boards provided easier access for calibration and repair reducing 'down time' for the instrument. In 1964, General Radio introduced the 1680-A Automatic Capacitance Bridge using a transformer ratio-arm bridge. Basic accuracy was ±0.1% over a capacitance range of 1pF to 1000uF at frequencies of 100cps, 400cps or 1000cps. We had adopted picofarad (pF) as 10^{-12} instead of uuF. Back to the 1680-A tester, dissipation factor was measurable from 0.0001 to 1.0 and 2 measurements per second were possible.

1680-A Capacitance Bridge

In 1969 General Radio released the 1792 Computer Controlled Logic Circuit Analyzer 'inventing' the automatic PCB testing industry. The term integrated circuits came into the public's consciousness in the 1970's. From that space research and the research of California companies surrounding Stanford University (later known as Silicon Valley), hundreds of transistors could be etched into silicon wafers to produce 'chips' the size of a postage stamp. Revolution took over the electronics industry. Automatic Testing Equipment (ATE) was now a booming business. Computer controlled instruments were THE wave of the future but analog bridge circuitry was still being used in some capacitance meters. In 1978 General Radio (now GenRad) introduced the first automatic test generation software for in-circuit testing called GenRad 2270. This software greatly decreased test program prep time. GenRad would soon switch its focus to test automation and diagnostics. Software was now the major driving factor in the design of new instrumentation.

Silicon Revolution & Digital Signal Processing


1659 Digibridge

Silicon Valley exploded in the 1980’s when integrated circuit design became ‘VLSI’ (very large scale integration) design. Literally thousands of transistors could now be produced on a chip the size of a human fingernail. This became commercial technology – available to all industries such as computers, medical instrumentation, imaging equipment, biotechnology and artificial intelligence. Hewlett Packard was the powerhouse in test instrumentation design and manufacture. Although concentrating on software automation, GenRad still manufactured capacitance instrumentation. A patent issued in January 1980 for the GenRad DigiBridge™ resulted in the manufacture of the highly accurate 1600 line of digital bridges that employed a synchronous detector circuit solving the automation difficulties of the former balanced bridge detector. Capacitance measurements from 0.00001pF to 99999uF with a basic accuracy of 0.02% over 500 programmable test frequencies (12Hz to 100kHz) were attainable. High-speed options were available increasing test speed to 30 measurements per second or 50 measurements per second depending on model.


7400 Precision LCR Meter

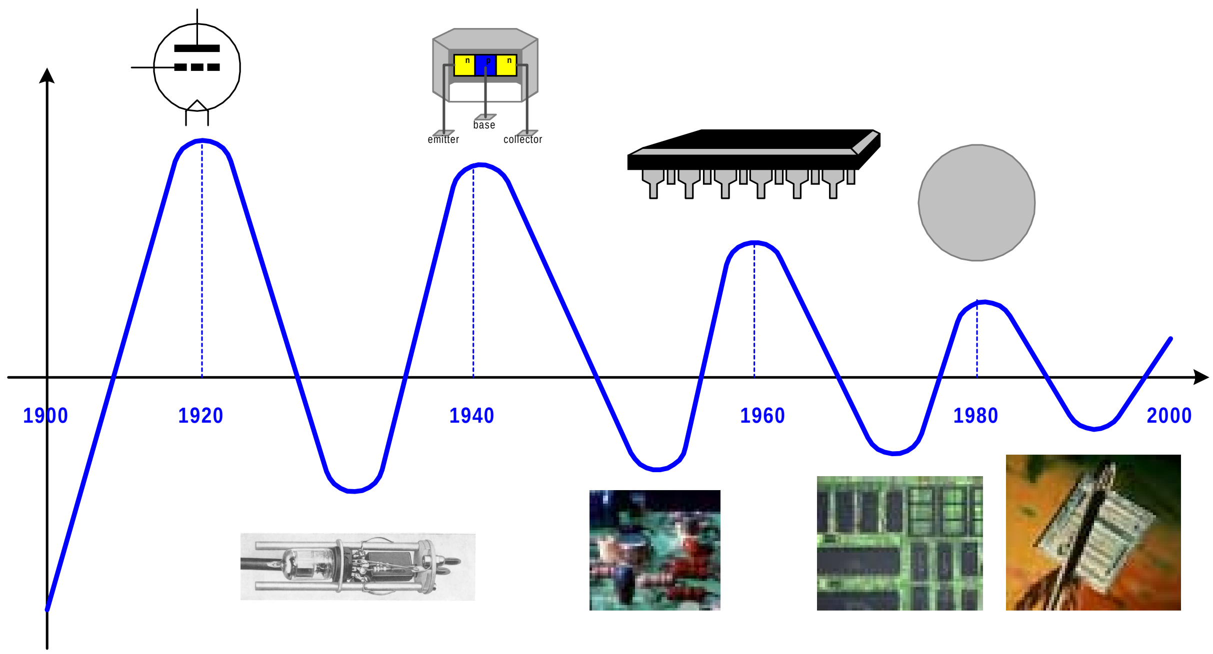
Digital signal processing (DSP) techniques were commonly employed in 1990’s instrumentation design as IC cost decreased. Digital sine wave generation, digital sampling and synchronous detection increased not only the speed of the capacitance measurement but the measurable range of frequency as well. Accuracy of the QuadTech (formerly GenRad Instrumentation Line) 7000 Series Precision LCR Meter was 0.05% over the range 10Hz to 2MHz at a speed of 1 measurement per second. To trade accuracy for speed one need only select FAST mode to make 40 measurements per second at an accuracy of 0.5%. Versatility in capacitance measurement instrumentation was key as the specific test application took precedence over design bells and whistles. Production line applications were interested in speed with a basic accuracy. Standards Laboratories and R&D Centers were more interested in highly precise measurements at very specific frequencies.


1930 Capacitance Meter

Here we are in 2001. Instrumentation design engineers are designing to customer specification. Capacitance measurements are being made in Quality Control labs on the materials (such as tantalum powder) that comprise the finished product before assembly to ensure the dielectric meets the end-users rigid requirements. Production Lines need capacitance instrumentation to meet international and national testing standards. New equipment design, automation and reduction of cost have brought product manufacturers the best in LCR instrumentation. Today’s new equipment provides the most essential passive component tests all in one convenient box. The ability to reconfigure the hardware and software of an instrument is especially useful in a production environment for making the box fit the test. Programming and remote capabilities allow full device characterization with the push of one button.

Progress Summary

We have come a long way in measuring capacitance. From the triode and vacuum tube to the bipolar transistor and printed circuit board. The advances in materials especially the silicon revolution has enabled electronic circuitry the size of the thread of a needle. Gone are the bulky steel condensers and transformers only to be replaced with microscopic silicon chips consisting of multiple circuits. Measuring instrumentation now consists of the small precise components and fast digital logic for highly accurate results over increasingly wider ranges.



So we have gone from Faraday's pen and ink drawings of electromagnetic lines of force to computer generated real time analysis of such data. Not such a bad rate of progress in a hundred and fifty years. Who would have thought Faraday's electro-chemical experiments proving 'different dielectric substances have unique and specific inductive capacities' could be measured, plotted, data extrapolated and interpolated with a single instrument today. We shouldn't take for granted this amazing odyssey in electronic theory and realization.

Research for this article found in:

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