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Synopsis

Some aspects of precision time measurements, controlled by means of piezo-electric-vibrators, as deployed in Germany prior to 1950.

For several centuries, time was controlled by means of mechanical clocks and chronometers which were, themselves, controlled by astronomical observations. In this country, Greenwich deployed one of the world's most important chronometers. Soon after the introduction of wireless in the early nineteen hundreds, special time signals were transmitted the impulses for which were derived from the best chronometers in the country.

Since the mid nineteen twenties, it has become possible to control clocks by means of piezo-electric-vibrators. For several decades following, those so-called quartz clocks were of a rather bulky nature and were mainly employed by astronomy centres to control their own time and frequency standards.

Though the scientific knowledge and technology of quartz was rather limited in the early days, it is very interesting to follow the improvements in quartz-clock technology and its specifications during the first half of the past century.

This paper describes the quartz-clocks designed by the German Bureau of Standards and the revolutionary quartz-clock invented by Rohde and Leonardt, of the Rohde and Schwarz company, in 1937. Also described is a very particular time measuring apparatus which was invented and designed by the Telefunken company specifically to check the range calibration of their radar equipment.

Introduction

Time is a rather mysterious quantity, whose physical existence nobody has ever seen and/or touched. But nearly every human being is, to some extent, aware of its phenomenon and has, from moment to moment, a rather subjective experience of it.

Even in physics it is not known what time really is, the only thing we can do is to construct apparatus with which we can compare (and so create) the time intervals. The “second” is the unit of time interval which is used in physics and which is the 86400 th part of the (average) daily rotation of the earth (24 x 60 x 60). These reference equipments were, in the past, often pendulum clocks which were succeeded, after about the end of the nineteen twenties and early thirties, by quartz controlled time standards. The first pendulum clock was patented (in Holland called octrooi) on 16 June 1657 and was invented by Christiaan Huygens. He probably wasn't the first one who worked in this field but it was he, without doubt, who brought the idea to maturity. (1)

Since about the mid 1950s we have been able to use, for this purpose, so-called atomic-clocks or frequency standards. However, for many decades previously, the electrical time-impulses were derived from the steady and cyclic movement of a pendulum which triggered an electrical (switching) contact. Those pendulum clocks were themselves compared with astronomical clocks as were, for instance, employed by the famous observatory in Greenwich. They probably used the world's best pendulum chronometer made by William Hamilton Shortt, the deviation of which was estimated at $\approx 1.5 \times 10^{-3}$ seconds per day. (2)

After wireless allowed the transmission of reliable time signals, most observatories in the world compared their time standards by radio. The accuracy of the time measurements could thus be increased to up to 10^{-8} (or even better). A disadvantage was that quite a long time interval was necessary, for even up to several months, to correlate the time data to obtain a sufficiently precise resolution.

From Lapis electricus to piezo-electricity

For this paragraph I am mainly indebted to the introduction chapter of Cady's famous book "Piezoelectricity". (3)
In 1703 a Dutch merchant stationed in Ceylon, reported in a letter to Holland a phenomenon:
- when a tourmaline stone was placed in hot ashes it first attracted and then repelled the ashes. This phenomenon was already known for many ages in India and neighbouring territories. It was sometimes called the "Ceylon magnet". In 1747 Linnaeus gave this phenomenon the scientific name "lapis electricus". Aepinus in 1756 noted the opposite polarities at the two ends of a heated tourmaline crystal. Brewster introduced the word "pyroelectricity" in 1824, after he had observed similar effects on various crystal types as well. (Cady, p. 1,2)

However, we had to wait until the brothers Pierre and Jacques Curie published, in 1880, their famous papers in the proceedings of the "Comptes rendus de l'Académie des sciences" in France.

1. Développement, par pression, de l'ectricité polaire dans les cristaux hémièdres à faces inclinées. (2.8.1880)

2. Sur l'electricité polaire dans les cristeaux hémièdres à faces inclinées. (16.8.1880)

(we have ignored the publications after 1880) (4)(5)(6)

They had observed that crystals (quartz and tourmaline) when compressed in particular directions showed positive and negative charges on certain portions of their surfaces, the charges being proportional to the pressure and disappearing when the pressure was withdrawn. It was Hankel who proposed (introduced) the name “piezo-electricity”. (piezo is the Greek word for to press) (Cady, p. 2,3)

Many scientists were fascinated by pyro- or piezo-electricity. It was the German (Prof.) Voigt who became, in 1910, most famous for his monumental *bible* “Lehrbuch der Kristallphysik”. (Cady, p. 5,8) According to Cady, Voigt proved (in his book) the differential equations for the elastic vibrations of the piezo-electric-vibrators. Many scientists were searching for a technique to explore the elastic vibrations in quartz crystals, though none of them had so far designed a working circuit.

Nonetheless, a decade later Walter Guyton Cady proved that the piezo-electric phenomenon could really control frequency stability.

Cady applied for an American Patent on 28 January 1920 which was granted on 3 April 1923 under number 1,450,246. He claimed a *Piezo electric resonator*, his second patent 1,472,583 claimed a *method of maintaining electric currents of constant frequency*, which was granted on 30 October 1923. Probably due to legal obstructions these patents were (had to be) re-issued (registered) in 1929. (7)

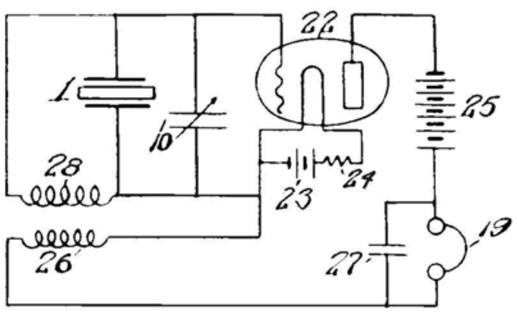

Fig. 1: Cady's first quartz oscillator application

On 1 October 1925 Cady filed another patent in this was claimed: *method of mounting piezo electric resonators for the excitation of various overtones.* Which was classified on 18 November 1930 under the patent number 1,782,117.

The wold’s first quartz filter (circuit) application is shown in fig. 2 which was, apparently, covered by Cady’s first patent as well.

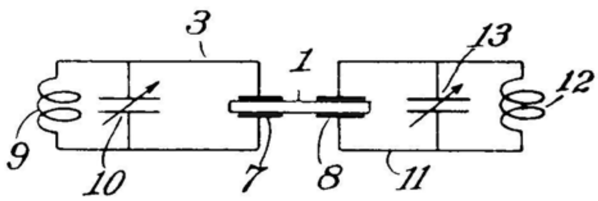

Fig.2: Cady's first quartz filter application

From now on it became possible to ensure frequency stability. However, its scientific nature wasn’t yet fully understood.

The second important patent was filed, in the name of George Washington Pierce concerning an “Electrical system”, on 25 February 1924 and which was classified 1,789,496. The two relevant circuit components were a quartz crystal and an oscillator valve. Originally Pierce placed the quartz between the anode and the grid of the valve. Miller modified its circuit (also called modified Pierce or Pierce-Miller circuit) and placed the quartz crystal between ground and the grid.

Terry attacked in a paper (1927) the conditions for stability of frequency of piezo oscillators. In the years that followed numerous papers covering other treatments of the theory appeared, each containing simplifying assumptions. One of the most thorough was that of Vigoureux (he died recently), who derived formulas for frequency and currents in terms of the crystal, valve, and circuit parameters. These were in good agreements with experimental results. (Cady, p. 506, 507)

We have seen, in the previous paragraphs, that the early technologies to explore the piezo-electric phenomenon mainly originated in the United States.

In closing this chapter we should also not forget the names of - Marrison, Mason, Hansell and others who played, for decades, a significant role in various American institutions. Pierce later turned his scientific attention mainly to the field of “magneto-striction”.

Germany’s contributions

The German Bureau of Standards which was officially known as “Physikalisch- Technischen Reichsanstalt” (or abbreviated PTR) was probably the first scientific centre in Germany which responded to Cady’s paper concerning his quartz resonator experiments published in the Proceedings of the Institution of Radio Engineers of 1922 .

Giebe and Scheibe of the PTR accepted the challenge of this new technology and became leaders in Germany, in the field of frequency and time standards. In the 1920s and 1930s their patents were widely perused even in this country.

Their first (main) attempts were carried out with quartz bar resonators. These quartz bars, or rods, were longitudinal vibrators whose long-axis was parallel to the X- or Y-plane of the quartz crystal. (Cady p. 463) Their first important innovation was to place a quartz bar (which had either a rectangular or sometimes circular cross section) inside a glass envelope incorporating a mixture of **Ne**on and **He**lium at a pressure of only a few millimetres of mercury (Hg). Assuming that the quartz crystal is mounted in an appropriate manner (with low damping) the local strains can become so strong that the piezo-electricity can ionize the Neon and Helium mixture which produces a visible glow (like an aura) around the centre(s) of action. For those cases where no high accuracy was required these luminous crystals were used as a secondary frequency standard and became, in the late nineteen twenties and in the early nineteen thirties, very popular. Its simplicity of operation is evident. It could load an inductive link or be connected by a small capacitor onto the antenna of a transmitting system. Its power consumption was very low and did not result in detuning of the (feed) source. Soon, several quartz bars were placed inside one envelope so that more than one frequency could be controlled or measured. However, a special phenomenon could manifest itself during luminous effects. The luminous quartz device could generate a squinched kind of tone modulation. This erratic behaviour was dependant upon the surrounding pressure and the mixture of the Neon and Helium gas. (8)

In the early days they used rather low, fundamental, quartz frequencies for luminosity purposes. An advantage was that its behaviour, at overtones, could be observed very well. As we have previously mentioned, the damping of a quartz resonator is an important parameter. Giebe and Scheibe became masters of the so-called “wire cord mountings” in which the quartz bars were bound or fixed at their nodal points in a very particular (probably patented) manner. They used for these structures silk or equivalent wire cords. The electrodes were capacitively coupled with the quartz bar, thus not touching its surface so as to enhance the Q -factor of the quartz resonator. (see later fig. 4 a-b)

Giebe and Scheibe’s efforts were carried out on behalf of the PTR, but these luminous or so-called “Leuchtquarze” were (probably for legal reasons) manufactured by the Radio-Frequenz GmbH, which company was a subsidiary of the Loewe-Radio company. In the 1930s Loewe became the major supplier of these luminous devices. However, due to political implications in the “Third Reich”, the affiliated brand name “Opta” also appeared at a later date.

The first British reference to the luminous quartz devices which I have been able to trace was published in Experimental Wireless & The Wireless Engineer of November 1926 (p. 658-660). It describes the Berlin Wireless Exhibition of that year quite extensively. Photographs of luminous quartz resonators, excited in various overtone modes, were shown even encompassing the 21st harmonic.

In the 1920s it became necessary to compare the frequency standards and measuring methods of the national institutions of standards in the civilised world. In 1926/27 the American BOS (Bureau of Standards, as it was named by Giebe and Scheibe, probably this institution is equal to the well known NBS later named NIST), and the NPL in this country, the TM in France and the IE in Italy started to cooperate in this field. Dellinger was also involved in the international group of frequency standardisation on behalf of the BOS in the US. Some of the standard devices and/or apparatus were sent to their fellow centres in the rest of the world. A funny detail in their paper is: - that the Germans sent their “quartz plate (probably bar) number 15” from Germany to America and then it went via England - France to Italia and back home. Whereas, the quartz plate number 16 travelled in the reverse direction. (9)

The Germans were not only focussing on quartz bar resonators but were also experimenting with quartz plates. Their aim was to enhance the quality of their frequency and time standards.

The Quartz-Clocks

Marrison of the Bell Labs had started to work already, in 1924, on the development of a quartz controlled clock which culminated (in 1929) in a mature quartz-clock. Its short term frequency stability was estimated at $\approx 5 \times 10^{-8}$ and it showed an average daily time deviation of $\approx 5 \times 10^{-3}$. According to Petzhold, these details were based on Marrison’s paper “The crystal clock”, in the Proceedings of the National Academy of Science of the United States, July 1930.

In September 1932 Scheibe and Adelsberger gave a paper called “Eine Quarzuhr für Zeit- und Frequenzmessung sehr hoher Genauigkeit”, at the German annual Physics meeting. (10) Which can be translated: -A highly accurate quartz-clock for time and frequency measurement. (Giebe died in early nineteen thirties)

They explained that, after an experimental period, their first quartz-clocks (model I and II), at the PTR, had been running since January/February 1932. Their time base, as this is called today, used a 60 kHz longitudinal quartz resonator which was housed in an evacuated glass envelope. (see also fig.4) They explained: - that to keep the daily time deviation of the clock within ± 1 ms the temperature stabilisation had to be controlled at ± 0.002° C. This was done by using a double temperature controlled housing, the quartz crystal being kept at 39 °C (some others at a different temperature).

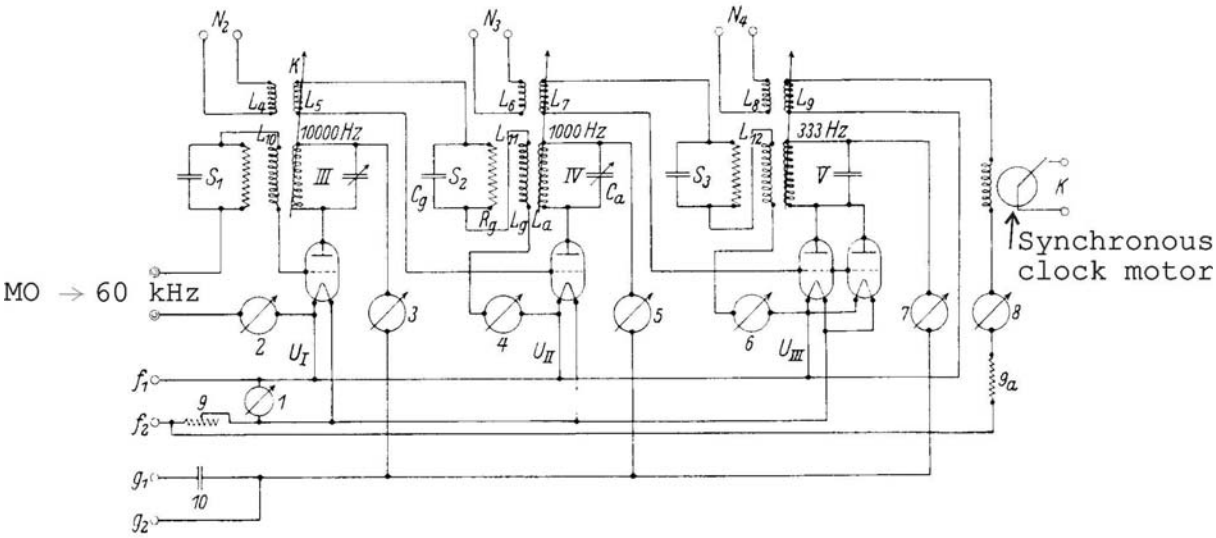

Fig.3: The divider circuit of the PTR clocks (1934)

The frequency of 60 kHz was first amplified and then fed onto a factor 6 divider stage making it 10,000 Hz; this was followed by a factor ten divider stage producing a 1000 Hz signal; this signal was then divided by 3, resulting ultimately in a 333 Hz signal.

Those dividers were of the so-called reactive type. An inductively coupled generative feedback stage was phase-locked by the in-coming signal from a higher frequency order. Those divider types were widely used in those days but were a bit difficult to operate due to the delicate tuning required to obtain stable synchronisation.

The 333 Hz signal was fed onto the synchronous motor of a clock which also generated the 1 second (= 1 Hz) time (interval) impulses. These time impulses could be compared with the astronomical signals which were sent by the wireless stations of, for instance, Nauen, Greenwich and the **B**ureau **I**nternational de l’**h**eure in Paris (after late 1987 BIH was renamed in BIPM which stands for **B**ureau **I**nternational des **P**oids et **M**esures) It soon proved that even these highly respected institutions didn’t supply coherent time signals. We will cover this point later.

These early quartz-clocks were rather bulky instruments though their specs were very good for those days. After an observation period of six months clock number I showed an absolute time deviation of 2 ms which was equal to a frequency deviation of ≈ 2 x 10^{-8}. However, comparison of the time or frequency constancy, over the same time period, for both clocks I and II showed a time difference of ≈ 0.3 ms which is equal to ≈ 4 x 10^{-9} (Hz).

The rotation of the clock (spindle) system showed daily deviations of ± 0.0003 s which is equal to a frequency tolerance of 4 x 10^{-9}. Statistically (absolute Gangkonstanz), those clocks were better than ± 1 ms which is equal to a frequency deviation of 1 x 10^{-8}. (Adelsberger and Scheibe, p. 839) We still have to consider that the only available time references, world wide, were the astronomical chronometers and, consequently, the wireless time signals which were transmitted by them.

In 1934, Scheibe and Adelsberger published a paper in a well respected German technical magazine entitled: - Die technischen Einrichtungen der Quarzuhren der Physikalischen-Technischen Reichsanstalt, which can be translated as: The technical installation of the quartz-clocks of the PTR. (11)

Their explanation of the quartz resonators which they had used was quite detailed. The quartz bar was 91 mm long, 3 mm width and its thickness was 1.5 mm. The bar orientation was parallel to the X-axis and its width was parallel to the Y-axis (zero-angle cut). The quartz bar and its electrodes are shown in fig 4a. Fig. 4b shows an example of the wire cord mounting.

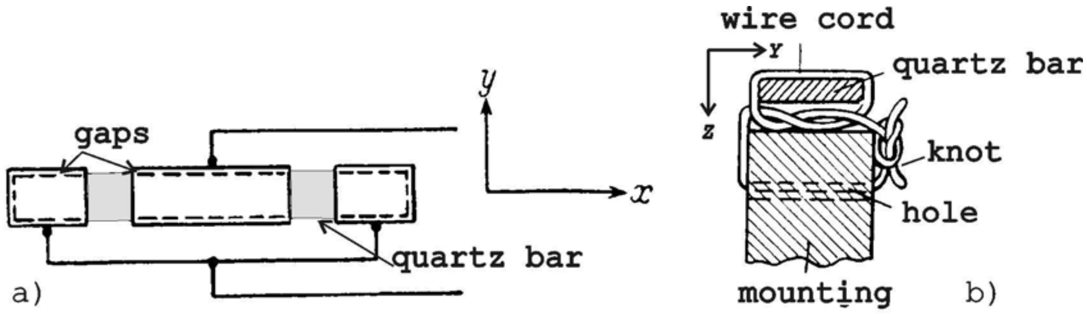

Fig.4: a) The quartz bar and its electrodes
b) Giebe's and Scheibe's wire cord mounting

In the meantime (1933/34) they had constructed two new clocks numbered III and IV the latter one being slightly different in design (in fact all showed differences due to modifications). Their quartz resonators and accompanying thermostats had also been improved as well. The switching intervals of the inner as well as outer thermostats were monitored by (ordinary) mechanical "telephone counters". The clock outputs were each fed on to an electrical time recorder. For their statistical survey it was very important to compare the time data which was generated by the astronomical centres with that of their own systems.

The (divided) signals of 10,000 - 1000 and 333 Hz (see fig.3) were available at their measuring outputs. The 10,000 Hz signals were also used to compare the output signals against the other quartz-clocks so as to generate beat notes which were caused by the phase drifts between the quartz-clock frequencies. By this means it was easy to create, and calculate, statistical time and/or frequency deviation graphs.

The first statistical proof of the deviations of the daily earth rotation

In 1936, Scheibe and Adelsberger published their quite revolutionary paper(s) called: "Schwankungen der astronomischen Tageslänge und der astronomischen Zeitbestimmung nach der Quartzuhren der Physikalischen-Technischen Reichsanstalt". Translated: Deviations of the astronomical length of the day and the astronomical time measurements using the quartz clocks of the PTR. (12)

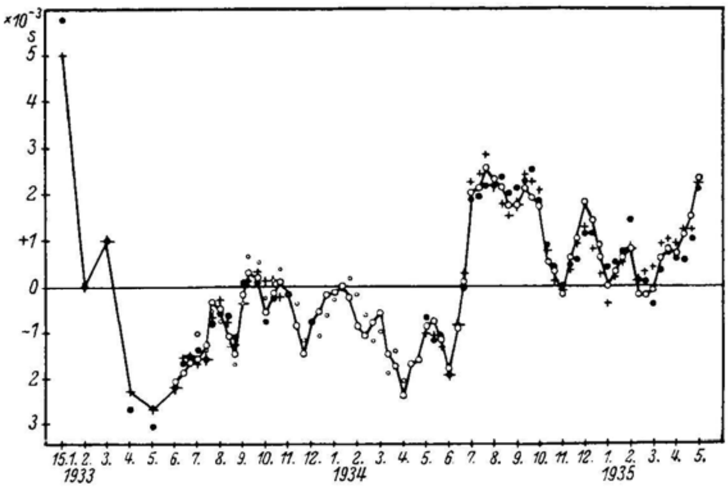

Fig.5: Deviations of PTR quartz clocks versus astronomical time

After explaining all kinds of particular system details, they proved, in figure 5, that the long term time deviations (January 1933 up to May 1935) of the three compared quartz-clocks showed only marginal mutual deviations in contrast to those of the astronomical time signals. This was a very important pre-condition to show that, when time differences were being measured between the astronomical centres and that of their own systems, these deviations (differences) could not be originating from their own systems.

Fig. 5 shows clearly that there were significant time deviation peaks around the months of May and lesser time deviations in the autumn periods.

Stoyko, in a controversial polemic claimed in his paper: - "Présion d'un Garde-Temps Radio-Electrique à Quartz" (13), - the assumption that the astronomical time generated by the pendulum chronometers would not be entirely correct was not valid. What he meant was, that the quartz-clocks were not as good as the astronomical clocks. We are not going to pursue Stoyko's assumptions. Adelberger made it clear that Stoyko's presumptions were not cogent, because Stoyko compared the results of only one astronomical clock (presumably that of the Bureau International de l'heure in Paris) against the time registrations of fellow astronomical centres. Challenged by Stoyko's statements, Scheibe and Adelsberger decided to seek to prove the real existence of deviations in the daily earth rotation. Up until then the time registrations were based upon the observations of the sun, or fixed stars, when these were crossing a particular meridian (longitude). These observations were, among other factors, subject to errors caused by the observer.

One of their conclusions was: - that their comparison of the quartz-clocks and the chronometers (chronographs) of the astronomical centres indicated that the quartz clocks, over a 30 day period, had a daily deviation of only ± 0.0002 s, which was about 4.5 times less than that of the, average, astronomical controlled pendulum chronometers (≈1 ms). Which latter value wasn't denied in Stoyko's paper.

We will not go into details about Scheibe and Adelsberger's proof concerning the stochastic deviations of the daily earth rotations.