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The Trochotron Beam-Switch Counter

Abstract

The Trochotron™ was a true miracle of ingenuity, a divide-by-ten high-speed counter in a single vacuum tube, fully exploiting the combined influences of magnetic and electric fields on electrons moving in a complex electrode structure designed to have ten stable states. Military appreciated its intrinsic reliability, a single tube replacing dozens of components and parts, when they still looked with suspicion at semiconductors. Soon it disappeared, early victim of the migration to solid state solutions.

Sommario

Il Trochotron™ fu un vero miracolo di ingegno, un singolo tubo che contava per dieci ad alta velocità, la cui complessa struttura era progettata per esibire dieci stati stabili e che sfruttava appieno le influenze combinate di campi elettrici e magnetici sugli elettroni in movimento. Per la sua affidabilità intrinseca rispetto all'uso di componenti meno complessi fu apprezzato specialmente dai militari. Presto scomparve, tra le prime vittime della migrazione verso lo stato solido.

The Trochotron™, overview of its developmental steps

Trochotron was the name associated to little-known hot-cathode counter tubes introduced for the first time in 1954 by Ericsson and then perfected by the Burroughs Corporation. In this device, electrons move along trochoid-like trajectories, under the effects of combined electric and magnetic fields, in a complex system of electrodes typically designed to operate with ten stable states. Probably it was the by-product of investigation underway since the 1940s at Bell and other companies on fast electronic step switches, to replace the stepping relays in telephone exchanges. In the Bell System Technical Journal, April 1944, an article described a radial beam device designed to operate as a 30-line multiplexer/demultiplexer [1]. The author, A.M. Skellett, gave details on electron beams directed by magnetic fields in a cylindrical system of electrodes. In Electronics, August 1951 [2], General Electric detailed a complex 25-line multiplexer, electrons being focused and directed by an external magnetic field, perpendicular to the cathode. Since the magnetic focusing generated a double-ended beam, the number of grid systems was doubled, each input-amplifier driving a pair of opposite grids. Five years later, the JETEC Council would register to National Union the couple of beam switching multiplexers shown in Figure 1: the 18-line electrostatic deflection 6090 and the 25-line 6324 with magnetic deflection, similar to the one before described by General Electric. National Union also announced in 1954 the unregistered line of Inditron™ neon indicators and in 1955 the 10-position beam switch LBS-1 with electrostatic deflection, in Figure 1. None of the said switches had intrinsic stable states, all relying upon external sequencers to direct the beam.

Fig. 1 - From National Union, the 6324, the 6090 and the LBS-1 multiplexers and the GI-21 Inditron™ numeric indicator.

Various research lines were also underway in Europe to design selector tubes with stable states capable of switching on clock pulses. Gas-filled counters in Figure 2, also known as Dekatrons™, proved simple to build but operated at low clock frequency, typically 4 kHz for many types. Philips had designed its exclusive E1T/6370 counter, also in Figure 2, its beam being electrostatically deflected. Unfortunately, its counting speed was quite low, 30.000 pulses per second, and the recommended circuitry was complex and considerably critical.

Fig. 2 - Two ETL Dekatrons and the Philips E1T / 6370.

A further line of investigation was based on the theoretical study developed by the Swedish physicist Hannes Alfvén who, along with Harald Romanus, had described in Nature, November 1, 1947 linear counting structures based upon trochoidal trajectories of electrons moving in combined electric and magnetic fields [3]. Several prototypes were experimented with, some of which described by the same authors in an article appeared in Tele-Tech, June 1954 [4]. The article shows fast matrices of linear switches and gridded coaxial geometries, also predicting solutions that would be implemented years later, such as magnets or load resistors moved into the glass bulb. In 1954 Ericsson started manufacturing the first coaxial trochotron, the RYG 10, in Figure 3. Details can be found in its datasheet [5] and in an article from the Ericsson Review [6]. Its basic sleeve-anode two-electrode structure is also described in (Millman e Taub, 1956).

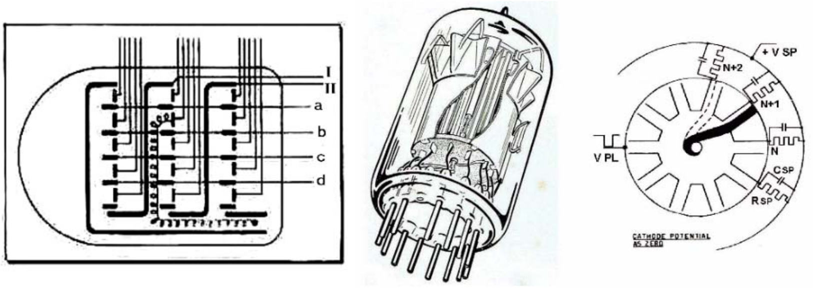

Fig. 3 - A matrix selector by Alfvén, the RYG 10 and representation of its electrodes.

It was a crude design, yet it could operate as divide-by-ten counter characterized by stable states. As shown in Figure 3, no grid was available and negative counting pulses were directly applied to the common anode, forcing it to zero in order to release the beam from the current spade. Its operation appeared quite critical. It was necessary to balance voltages and time constants of the spades as well as the intensity of the magnetic field so that the electrons could follow circular trajectories at a given speed along equipotential paths. At the same time, the shape and duration of negative pulses had to be compatible with the flight time, the time necessary for the beam to be released from the current spade and approach the zone of influence of the next one. Once the proper parameters were selected for a given frequency, pulses had to be shorter than 0.8 CV/I, whereas C and V were the spade capacitance and voltage and I was the cathode current, otherwise one or more spades were skipped [7]. Few years later Ericsson would abandon this design for the three-electrode one perfected at Burroughs.

In the mid-fifties a single decade counter made use of many components. The counter module type AC-4D-95 in Figure 4, used by Hewlett Packard in the 1 MHz counting chain of its 524 frequency meters [8], required four twin-triodes. Even more complex was the 10 MHz counter, with eight high-frequency pentodes.

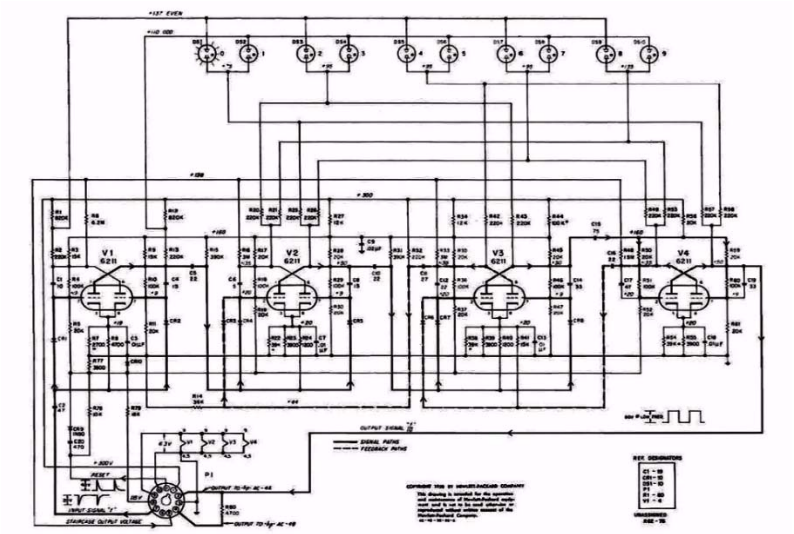

Fig. 4 - Schematic diagram of the HP AC-4D-95 decade counter module.

In 1955, an old firm was ready to enter the scene of electronic digital counters. The Burroughs Corporation, founded way back in 1886, was a leading manufacturer of electro-mechanical accounting machines. To approach the new emerging market it had hired Saul Kuchinsky, who moved from National Union to the Burroughs Research Center in Paoli, PA. In 1954, Burroughs also bought a small tube manufacturer, the Haydu Brothers. In Plainfield, NJ, George and Zoltan Haydu had been in business since 1936, manufacturing precision mechanical parts for the vacuum tube industry: electrodes, spacers, electron guns, anode blocks for magnetrons, glass-blowing machinery, up to small runs of special tubes for large manufacturers.

The first commercial beam-switch counter, the MO-10, was the result of joint developmental work involving Fan and Kuchinsky at the Burroughs Research Center and the Haydu Brothers, as a subsidiary of Burroughs itself. Almost certainly its design was inspired to the Alfvén work, solving the critical issues of the Ericsson RGY 10. Control grids and separate anodes were used and the current distribution to the spades was increased. A preliminary announcement of a still unnamed «beam-switch tube […] perfected by the Burroughs Research Center and precision manufactured in production quantities by the Haydu tube division» appeared in May 1955 in Electronics [9]. The MO-10 was registered as 6700 to Haydu Brothers in June 1955, RMA record 1485, see Figure 5. It was referred to as “Haydu Magnetron Beam Tube” in the July 1955 issue of Electronics magazine [10].

The announcement of the low-voltage variant H-B 101 appeared in Electronics, December 1955 [11]. The counter, designed for airborne operation at 26 volts, was shown aside a preliminary view of a Nixie™ numeric indicator. In February 1956 the H-B 101 was registered to Haydu as 6701, RMA/JETEC release 1589. In beam-switch tubes the magnetic field was generated by a cylindrical permanent magnet surrounding the glass bulb. For operation close to cathode-ray tubes or other devices sensitive to magnetic fields, variants with external mu-metal shields were introduced, some unregistered too. The BD-301 shielded counter in Figure 6 was specified for operation up to 2 MHz and registered in May 1961 as 6703. The RMA record 3295 also reports the code 6704, assigned to the high-speed MO-10R, shown in Figure 5, capable to operate up to 10 MHz thanks to built-in spade load resistors.

Fig. 5 - From left, an early Haydu badged 6700 tube, a later sample with Burroughs label, a low-voltage 6701 and the high-speed MO-10R/6704.

Fig. 6 - From left, the shielded BD-301/6703, the more slim BD316, the BD-401 noise generator and its smaller successor BX-1203/6713.

Several circuits were proposed, using these devices in various applications, as modulo-n counters, event counters, rangefinders and navigation equipment, coding and decoding sets, storage blocks or even as analog signal multiplexers. Partially depopulated types were proposed as pseudo-random noise generators. Being used in secret radar jammers, the registration of the wide-band noise generator BD-401 as 6702 was delayed until February 1964, taking place at one time with its successor, the more compact Beam-X type 6713/BX-1203. Shielded types were quite large, about 60 mm in diameter. The more compact BD-316, in Figure 6, was then proposed, with thinner electrodes into a glass bulb whose diameter was decreased just above the base.

The variety of trochotron tubes grew in the early sixties with the introduction of the new 'Beam-X' family [12]. The design of the electrodes was modified, moving the source of the magnetic field into the glass bulb. As shown in Figure 8, ten magnetic rods replaced the anode strips, acting as targets while concurring to generate the proper magnetic field. The outer diameter of the unshielded 6710/BX-1000 Beam-X trochotron was only 30 mm, compared to the 44 mm of the 6700 and the 58 mm of the shielded 6703. Burroughs also introduced variants with increased current drive capability as the 6712/BX-3000, shielded types as the BX-2005 used in some Rank Xerox copiers, and also low-voltage variants as the BX-4000 proposed for airborne applications.

The basic design and its operating principle

For each count position the trochotron made use of the three-electrode structure devised by Fan and Saul Kuchinsky at the Burroughs Research Center in Paoli, PA. To understand its operating principle, we refer to the Figure 7, which shows the internal structure and typical connections of a trochotron. An inner ring of ten V-shaped electrodes or spades, one for each counting position, surrounds the cathode. Ten "L"-shaped output plates or targets, from "0" to "9", are all around, partially shadowed by the corresponding spade. A grid rod is between each target and the successive spade. All odd grids are connected together to a base pin while all even grids go to another pin. Typical supply voltage of 200 volts is required, but some types with low magnetic field were specified for 26-volt operation. Targets are fed through load resistors of relatively low value, the value of load resistors to spades being higher, 100 kΩ or more. The glass bulb containing the described electrode structure is immersed into a cylindrical magnet, flux lines being parallel to the cathode itself.

Out of the typical conditions given in the data sheet, this tube has several modes of operation, even oscillating ones. Here we try to give an intuitive description of its operation as counter, according to the notes of the same Kuchinsky [13]. At power-on, under the combined influence of the external magnetic field and of the electric field generated by the ten spades, the tube is in a cut-off state. Electrons are forced by the magnetic field to follow quasi-circular equipotential orbits in a dynamic equilibrium, in the region between spades and cathode. Due to their curved trajectories and to the shape of spades, influence from the targets in the background is almost entirely masked off.

The initial zero condition is set by pulsing low the S0 spade for a short while. Electrons spiraling in its vicinity now feel the influence of the electric field from the target T0 behind, trajectories being modified due to its attraction. Subsequently their flow deviates to T0. Due to the curved trajectory, about 15% of total electrons hit the spade S0, holding its potential low even after the reset pulse. The resulting current distribution to the target T0 and the spade S0 is roughly illustrated by the dotted path starting from the cathode in the Figure 7. This is a stable state, the current through the selected target being in the order of a few milliamperes.

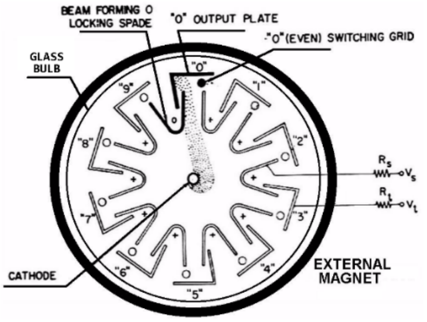

Fig. 7 - Arrangement of electrodes in a divide-by-ten trochotron, with supply connections.

Fig. 8 - Beam-X counters. From left, cross section of the family, the 6710/BX-1000, the high-current BX-3000 and two shielded types, the BX-4000 and the BX-2005.

In typical counting applications the switching grids are driven by a bi-phase sequencer which supplies negative pulses alternately to the even and to the odd grid groups. When a negative pulse of suitable amplitude is applied to the grid close to the holding spade, it counteracts the attraction of the selected target, releasing the beam from the target itself. Repelled electrons, due to the rotating trajectories imposed by the magnetic field, move then to the leading spade. The current increase through the spade cause a remarkable drop of its potential and the beam is then attracted by the corresponding leading target in the background. A new stable condition is then reached at each counting pulse.

Trochotron found several niche applications mainly in high speed counters, computers, navigation and military equipment. It was bulky and expensive when compared to gas counters as the dekatron, nonetheless it was capable of operation at frequencies as high as 10 MHz with fairly high output current drive. When visual indication of the count was required, the trochotron itself drove special neon indicators containing ten negative electrodes shaped as numbers from 0 to 9. Some types were built under license in Europe. The Mullard/Philips ET51, also listed as CV5277, was equivalent to the 6700, as shown in Figure 9. Ericsson (ETL) made several equivalent types, as the basic VS10G, its shielded variant VS10G/M, the high-current VS10H and the low-voltage version VS10GK.

Fig. 9 - The Mullard ET51 and the ETL VS10G compared with the Burroughs 6700.

Numeric indicators: Inditron™, Nixie™ and Pixie™

The trochotron does not give visual indication of the actual count. Due to the DC drop of the active target, its state can be easily detected using neon bulbs connected to each target. Early commercial numeric indicators were the Inditron™ types by National Union [14]. Not directly related to the trochotron, the family was advertised since 1954 for applications in elevators, scoreboards, clocks or game machinery. Ten rods of different length rose up from the base, each bearing a number-shaped electrode. The numbers were at considerably different depths, as visible in Figure 10, therefore reading several indicators side by side was rather awkward. Saul Kuchinsky had just worked at National Union before joining Burroughs as responsible for the trochotron development. The Nixie™ indicator, in Figure 10, was first announced as H-B 106 by Haydu in December 1955 [10] and certainly Haydu badged quantities were produced through 1956. Eventually it was registered as 6844 to Burroughs in January 1957. At that time George and Zoltan Haydu had left the direction of the tube factory, founding their new Haydu Electronic Products Inc. to continue manufacturing precision parts for vacuum tubes [15]. In the same month the double coded 6844/HB-106 was advertised in Electronics as the «newest star in the electronic galaxy». Actually this very compact indicator combined in the same short bulb ten neon lamps with common anode, closely spaced cathodes being shaped as numerals from 0 to 9. When cathodes were tied to the targets of a trochotron, only the one connected to the active target lighted up. Also, a Pixie™ indicator was proposed as low-cost alternative for the Nixie™. Here the anode was a disc punched with numbers 0 to 9, cathodes being short extensions of the pins below. Its indication resembled that of gaseous dekatron counters. Nixie™ indicators survived trochotron and other tubes, being in use well in the semiconductor age, until replaced by LED, LCD and VFD displays.

Fig. 10 - Two images of the National Union GI-21 Inditron™, the Haydu-badged HB-106 Nixie™ beside its box and the Amperex/Philips Z550M Pixie™ numeric indicator.

Typical applications

The ASE collection includes a couple of counters, both built around trochotron tubes. The first one is of particular interest since, being fully working and complete with its technical manual, it testifies the impressive circuit simplification obtainable with trochotrons. Our U.S. military FR-114U, part of AN/TSM-16 frequency meter in Figure 11, was manufactured around 1960 by Van Norman Industries. It accepts input signals from 20Hz to 1MHz. It actually shows, beyond the typical applications found in the scarce existing documentation, how clean a set designed around these tubes could be, even due to the simple surrounding circuitry required.

Count or frequency are displayed by six 6844 Nixie™ indicators, each driven by a counter module based upon the 6703, as the one in Figure 12. 1 MHz maximum frequency was specified for the set, even if the 6703 could operate to above 2 MHz. Each counter module interfaced through a couple of connectors, the top one to the corresponding display and the bottom one to signal and supply buses.

Fig. 11 - Images of the FR-114U frequency meter.

In Figure 12, the photo of a counting module with its diagram aside [16] show how simple a trochotron counter could be when compared to the diagram of Figure 4. Nixies are directly driven by the targets through short flat cables. Only four signals plus the power buses connect each module to the mainframe and to other modules, through the 6+6-way connector on the small double-sided printed circuit.

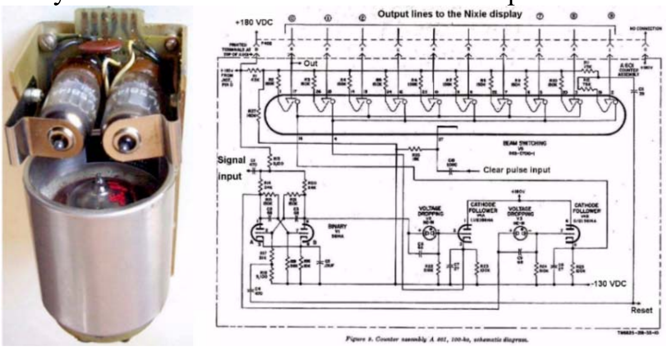

Fig. 12 - The decade counting module with its schematic diagram.

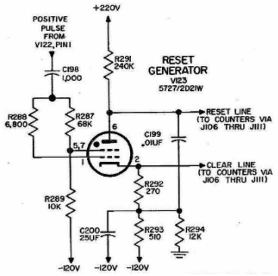

Fig. 13 - Schematic diagram of the reset sequencer.

Operation is controlled by a sequencer generating timing pulses for reset, count and display states. Before each count, two steps are required to initialize trochotrons: clear and reset. The positive clear pulse applied to cathode unlocks electrons from any target previously engaged. Each trochotron returns in the cut-off state and can now be initialized to its ‘zero’ count. This is accomplished by a negative reset pulse to the ninth spade S9. The same pulse also sets the input signal flip-flop to its ‘even position’, so that odd grids are negative and even grids are positive. Due to the polarity of grids and of the ninth spade, the beam skips the target T9 and locks to the next T0, ready to start a new count. Modules operate from +180 and –120 volts supply voltages. Total voltage, 300 VDC, feeds counters through 36 kΩ target loads and 18 kΩ cathode resistors. The spade resistors, 150 kΩ each, are tied to a voltage divider at about 100 V referred to cathode. The input signal is fed to the bi-phase counting flip-flop V1 which, through cathode follower buffers (V4A-V4B), alternately drives even and odd grids of the associated trochotron. The output signal to the next module is directly derived from the T0 target. A single 2D21 thyratron generates both the clear and the delayed reset pulses common to all the counting modules. The simple circuit of the pulser is shown in Figure 13.

In 1962 Lavoie Labs, Morganville NJ, advertised the most advanced frequency meter of that time, the 10 MHz LA-80, fully based upon trochotron counters. It had been engineered to be interchangeable with the HP 524, the counter widely accepted by the military to which refers the diagram of Figure 2. Probably at request of the same military the 20-inch high LA-80 also accepted the HP plug-ins.

Fig. 14 - The Lavoie LA-80 digital counter on the left and on its right the HP 5245L, here with the HP 5257 transfer oscillator plug-in.

Unfortunately, the LA-80 could well be seen as the swan song of the trochotron. One year later, in 1963, HP would have introduced its 5245L solid-state frequency meter, which only retained the Nixie indicators. In its compact cabinet, 130 mm high, this counter was capable of operating up to 50 MHz, also accepting optional prescaler plug-ins to measure higher frequencies. In a few years, soon after the introduction in November 1967 of the revolutionary HP 5260A PLL frequency divider, its measuring range would extend well beyond 10 GHz. The Figure 14 shows an image of the LA-80 from a Lavoie advertisement [17] aside the HP 5245L 50 MHz counter, here equipped with the 5257A plug-in, a transfer oscillator which extended the frequency measurement of the basic meter up to 18 GHz.

Conclusions

No matter how elegant and complex the trochotron principle was, no matter how much effort was needed to achieve a family of properly working and easily usable devices, no matter that man had gone into the space with technologies still based on vacuum tubes: there was no possible competition for trochotron against the now mature solid-state. After all, as early as 1968 the writer was buying for a few hundred lire apiece 7490 TTL decade counters, small integrated circuits specified for operation up to 10 MHz from a single 5V supply and readily made in any quantity by photographic processes.

Acknowledgements

Special thanks go to Tube Collectors Association, in particular to Bjorn Forsberg for his testimony on the assembly of the early bench circuits for the RGY 10 at Ericsson and to Martin Forsberg for his valuable information on the work of H. Alfvén.

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[17] Electronic Design's New Product Locator, 1962, page 359

Datasheets for Burroughs, Haydu, National Union and Philips tubes listed into registration records of the Radio Manufacturers Association, later Joint Electron Tube Engineering Council, are today preserved in the Tube Collectors Association Data Cache archive.

Webgraphy

Tubes and sets shown in the photos are today preserved in the ASE collection. The entire collection of counting tubes and of frequency meters can be accessed through the links below:

http://www.ase-museoedelpro.org/
http://www.ase-museoedelpro.org/Museo_Edelpro/Catalogo/tubes/T09_computer_hirel.htm
http://www.ase-museoedelpro.org/Museo_Edelpro/Catalogo/Overview/Index/M1-Signal Generators & Freq Meters.htm