A Digital Differential

Simultaneous Bi-directional Counting using a Dekatron

By W. H. P. Leslie*, B.Sc., A.M.I.E.E.

A new circuit is described using a Dekatron to indicate the running difference in count between two independent pulse trains. It is applied to indicate frequency differences—to generate difference frequency signals without tuned circuits—to control frequency or speed relative to a master signal which may originate from a quartz oscillator, wide range oscillator, or from a shaft whose speed has to be copied.

DURING the development of a precision speed control system[1] the electrical equivalent of a differential gear unit was required. The system was digital in nature, an indication of the difference in pulse repetition rate of a standard and a controlled signal being desired. A bi-directional uniselector switch was first used, following which the Dekatron circuits described below were developed to allow faster counting rates.

Normal Dekatron Operation

To describe the operation of the bi-directional counter it is necessary to review the normal operation of a "double-pulse" Dekatron (a more complete description can be obtained in the valve-maker's booklet[2]). The valve used, a GS10B, has a maximum counting speed of 5kc/s, although there has recently appeared the GS10C selector tube Dekatron suitable for 20kc/s.

In Fig. 1 the signal to be counted is applied to the grid of valve V_1, having been formed into positive pulses of 60μsec duration. The large 60μsec negative pulses generated at V_1 anode are applied to two potential dividers R_1R_2 and R_3C_3. R_1R_2 produces a similar rectangular pulse of half amplitude, while R_3C_3 produces an integrated waveform. The time-constant R_3C_3 is chosen so that the sloping front of the pulse has passed half amplitude at the end of the pulse; thereafter the waveform returns slowly positive.

The Dekatron contains an anode and ten counting cathodes. Between each pair of cathodes are two transfer electrodes T_1 and T_2. All T_1 electrodes are connected to one input terminal and all T_2 electrodes to another. Assume that the glow is on cathode 2 in Fig. 1, a signal pulse first makes itself known by a negative pulse on the ten T_1 electrodes. The particular T_1 nearest to the conducting cathode "2" strikes most easily since it is partially in the ionized gas around "2". After T_1 has started glowing it carries the anode potential down due to the fixed potential difference between the electrodes of a glow discharge. The reduced voltage between the anode and cathode "2" extinguishes the discharge that existed there. At the end of the transfer pulse T_1 returns positive and the glow transfers to the adjacent T_2 electrode which is being held negative by the integrated transfer pulse. As T_2 returns to its positive voltage the glow transfers to the nearest cathode which is now "3". In a normal counter the process repeats and the glow progresses round the tube in a clockwise direction in response to drive pulses. When anti-clockwise progression is required it is only necessary to connect the direct pulses (via R_1R_2) to T_2 and the integrated pulses to T_1.

Bi-Directional Drive

Fig. 2 shows how two sets of drive pulses can be supplied to valves V_1 and V_2 in order to produce clockwise rotation for V_1 pulses and anti-clockwise for V_2 pulses. When pulse trains are applied simultaneously to V_1 and V_2 the glow moves at a rate indicating the difference* in

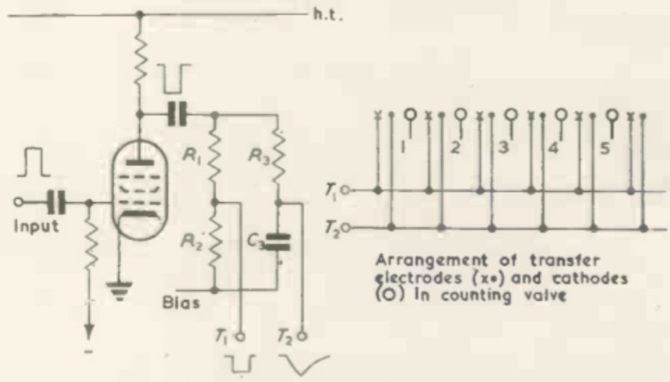

Fig. 1. Essential features of valve manufacturers circuit

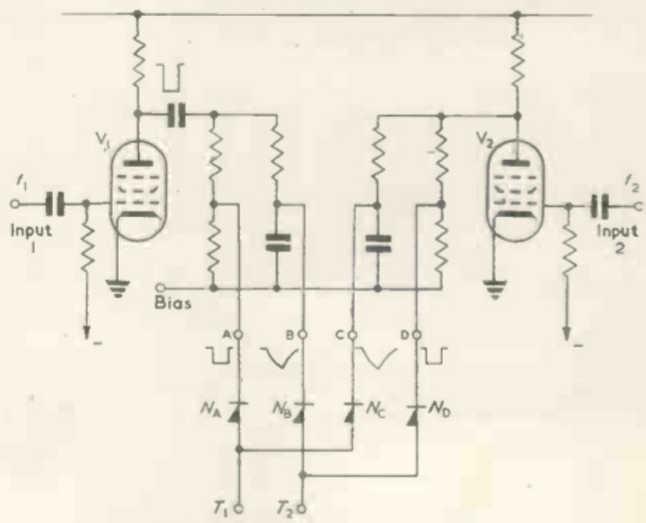

Fig. 2. Bi-directional counter drive circuit

frequency. To understand why the counter performs without error it is necessary to consider three cases:—

(1) Pulses at V_1 and V_2 occur interleaved but not at the same time; the glow advances for each V_1 pulse and returns for each V_2 pulse so that the net movement indicates the difference in count.

(2) Pulses arrive at V_1 and V_2 at the same instant. Thus pulses appear at transfer electrodes T_1 and T_2 at the same time and the glow (at cathode "2" say)

* *Mechanical Engineering Research Laboratory, D.S.I.R.*

* *Shortly after the circuit was evolved for this purpose by the author, it was published independently[3] by the valve manufacturer but the latter only offered it for alternative clockwise or anticlockwise counting. They made no mention that it would operate for simultaneous counting.*

spreads to either or both T_1 and T_2 electrodes adjacent to "2". At the end of the direct pulses both T_1 and T_2 are held negative by the two integrated pulses so that there is no glow movement. As the integrated pulses return positive the cathode nearest to the glow is "2" so the glow returns there. The net effect is no count as it should be.

(3) A pulse may reach V_2 during a V_1 pulse. The glow moves to T_1 first; when the direct pulse at T_1 finishes, the voltage does not return completely positive owing to the beginning of the integrated pulse from V_2; if the glow transfers to T_2 it returns again to T_1 after the direct V_2 pulse has ended. When the integrated V_2 pulse on T_1 ends the pulse returns to the cathode from which it started. The net effect of no count is correct.

Experimentally it is found that correct counting is obtained in all circumstances providing the pulses generated by V_1 and V_2 are of similar width. It is possible to apply two pulse trains of 2kc/s with a frequency difference of as little as 1 cycle in 10 seconds so that the glow moves slowly round the tube. Such a condition provides an effective method of setting one pulse width having set the other pulse train to give optimum counting speed.

Adding

Although the circuit subtracts without error it will not add correctly since coincident pulses from the two trains (with suitable cross connexion to T_1 and T_2) would only produce one count. To overcome this difficulty it would be necessary to delay any pulse which arrived during the active time of another pulse.

Output Signal Circuit

When the counter is to be used to generate an output it is necessary to make suitable cathode connexions. Figs. 3(a) and 3(b) show convenient methods of generating stepped approximations to sinusoidal and square waves respectively at $(f_1 - f_2)/10$ c/s where f_1c/s is the frequency of the signal applied to V_1 and f_2c/s that applied to V_2. Fig. 4(a) shows the voltage produced when $f_1 = 1\,000$c/s and $f_2 = 990$c/s. Fig. 4(b) shows the effect of adding a single smoothing capacitor of 0·05μF. Similarity Figs. 5(a) and 5(b) show the corresponding square waves.

Such an output can be applied to the generation of low audio frequencies of high stability. For example a range of 48 to 52c/s may be required as a master frequency for an alternator control or for calibrating a power frequency meter. In this case f_1 could be made 5 350c/s from a quartz crystal or tuning fork. f_2 could be made variable between 150 and 550c/s from a stable *RC* oscillator which can be purchased with an accuracy of ± 0·25 per cent and a half-hour stability of 0·025 per cent. The output would then range from 520 to 480c/s and after division by ten, using a normal Dekatron stage, would give 52 to 48c/s with an accuracy of 0·025 per cent and a half-hour stability of 25 parts in 10^6, adequate for many purposes. The *RC* oscillator can be checked accurately at 535c/s by dividing the quartz crystal frequency by ten using the Dekatron stage and comparing with the nominal 535c/s from the *RC* oscillator visually at the differential counter.

Limitations

The limitations of this method should be noted. It is only possible to get improved accuracy of the variable oscillator by restricting its frequencies relative to the fixed oscillator of better accuracy. This limitation is shared with other frequency mixers. The other limitation is due to the digital nature of the process. Consider a particular case when $f_1 = 25f_2$. In the absence of f_2 it takes 10 counts from f_1 to obtain one circulation from the glow; when an f_2 count subtracts one count the circulator requires 11 counts from f_1. Following this process step by step for the case considered it is found that the time for each cycle (circulation of the glow) in terms of cycles of f_1 is:

10, *a*, 10, 11, 10, 11, 10, 10, 11, 10, 11, 10, 10, 11, *a*, 10, etc.

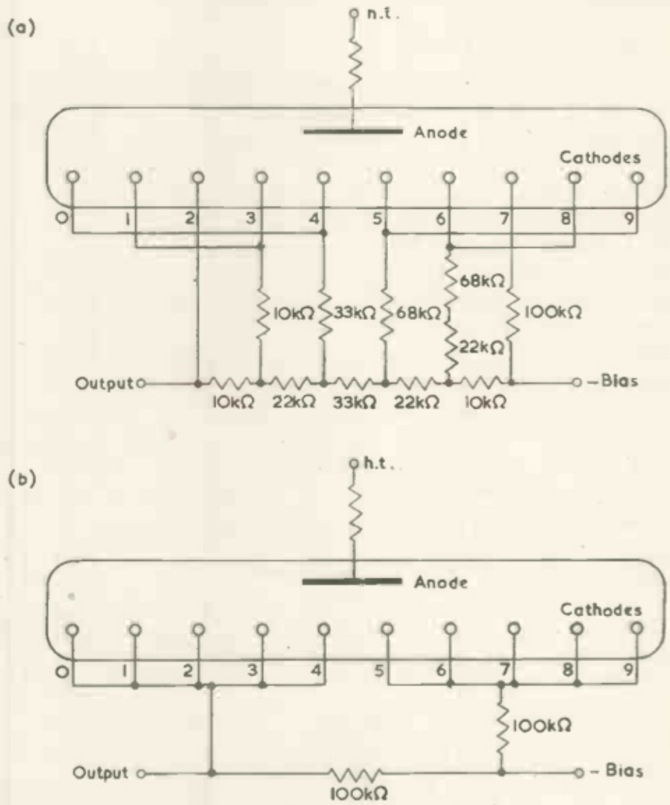

Fig. 3(a). Sinusoidal output circuit
(b). Square wave output circuit

Fig. 4(a). Sine wave circuit—no smoothing
(b). Sine wave circuit—0·05μF smoothing

Fig. 5(a). Square wave circuit—no smoothing
(b). Square wave—smoothing 0·05μF

where the times between "*a a*" repeat. Thus individual cycles vary in time by 10 per cent. The average length is (125/12) cycles so that the averaged frequency is $(24/250)f_1$. This is exact as $f_1 - f_2 = (24/25)f_1$ and the differential divides the frequency by ten. The cycle to cycle error is reduced to 1 per cent if the output of the differential is divided by ten in a normal Dekatron divider giving cycle times in terms of f_1 cycles of:

b, 104, 104, 104, 105, 104, 104, *b*, 104, etc.

and repeating between "*b b*". The average time is (625/6) cycles of f_1 so that the averaged frequency is $(24/2500)f_1$ an exact result.

This limitation has been discussed in some detail since it can easily be overlooked. For many applications where the frequency is averaged by inertia or smoothing circuits the divided output, as used to obtain the 48 to 52c/s signal above, will be acceptable. The effect is at its worst when there is one f_2 cycle for ten or more f_1 cycles. When f_1 and f_2 are nearly equal so that one output cycle takes say 1 000 f_1 cycles and 990 f_2 cycles the smoothed output cycles cannot vary by more than 0·1 per cent.

Output Control Circuit

It is when the circuit is used in a frequency or speed controller that it is most useful. In this application f_1 is a standard frequency, f_2 is the frequency to be controlled. Any error results in rotation of the glow in the tube. By disconnexion of cathode "0" so that the glow cannot rest on it the rotation is prevented at "1" and "9". Thus if f_2 is low in frequency the glow rests on "9" and if it is high it rests on "1". This is the effect obtained from a mechanical differential driving a pointer through a friction clutch, the rotation of the pointer being limited by stops. The position of the glow can be detected electrically by inserting resistors in the cathode circuits as shown in Fig. 6. When the glow is on cathode "9" the cathode current goes straight to negative bias producing no output voltage. As the glow moves along to 8, 7, 6 etc. the cathode current passes through more of the chain R_A to R_H producing progressively more positive voltages at the output.

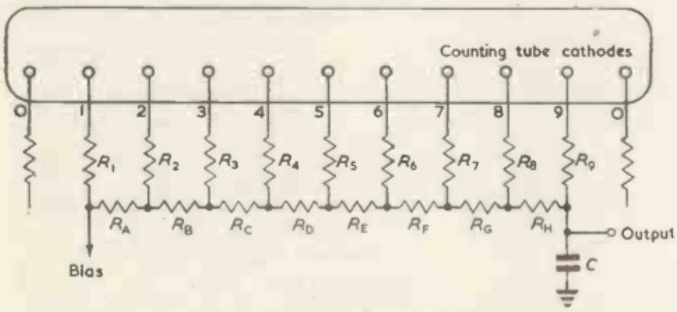

Fig. 6. Preferred output circuit

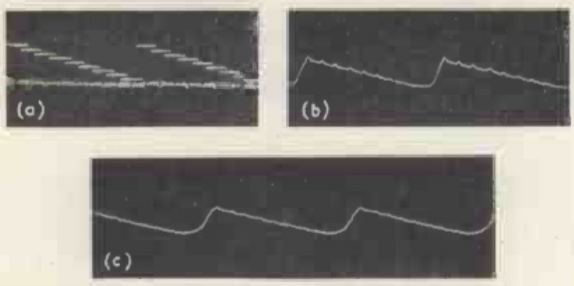

Fig. 7. Stepped output 980 and 1 000c/s applied
(a). Staircase output—no smoothing
(b). Staircase output—0·05μF
(c). Staircase output—0·25μF

With "0" connected to earth for testing, the network produces the stepped output shown in Fig. 7(a). The addition of a 0·05μF smoothing capacitor (C in Fig. 6) produces the output in Fig. 7(b). The output voltage can be taken to control the frequency or speed, raising f_2 when towards "9" and lowering it when near "1". The glow then settles on the step which causes equality between f_1 and f_2. It would appear unfortunate that only 9 steps of voltage are available but the actual control process gives infinite variation in output. The f_1 and f_2 pulses interleave so that each f_1 pulse increases the count say from "4" to "5" and each f_2 pulse decreases it from "5" to "4". The glow appears to rest on the two cathodes and if more output voltage becomes necessary (to maintain speed due to increased load for example) the relative phase of the two signals will alter to give a longer dwell on "5" and a shorter dwell on "4" increasing the average voltage. Fig. 8 illustrates the process: 8(a) shows a steady condition giving a voltage on cathode 2 and mainly on cathode 3; 8(b) shows the glow on cathode 3 (*drive pulses exactly in phase*); 8(c) shows the glow mainly on cathode 3 with brief excursions to cathode 4 so that the average voltage is just greater than corresponds to cathode 3 alone; 8(d) shows the glow still on cathode 3 but now mainly on cathode 4.

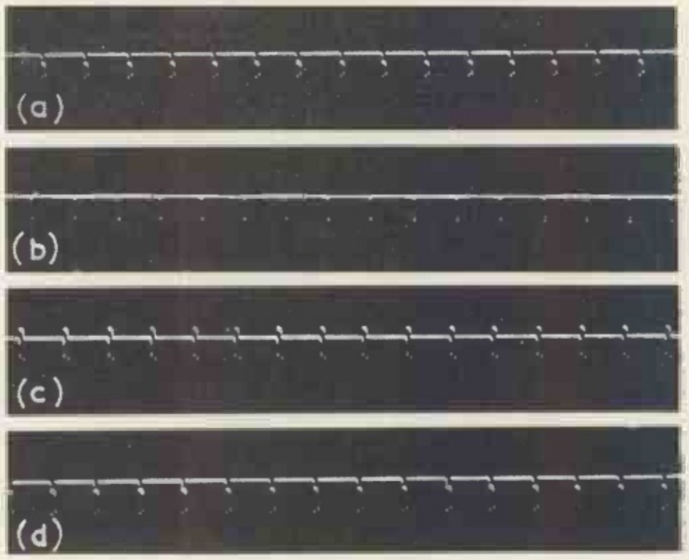

Fig. 8. Output variation between steps both frequencies 100c/s, phase varied
Fig. (a). On cathodes 2 and mainly 3
(b). On cathode 3
(c). On cathodes 4 and mainly 3
(d). On cathodes 3 and mainly 4

Conclusion

It can be seen from the above discussion that the electronic differential possesses the desirable combination of coarse control (speed grossly high or low) with fine control (phase locking). Most existing speed control systems have considerable difficulty in maintaining the accuracy of the coarse control over a range of speeds so that it brings the speed within reach of the fine controller. A motor speed control utilizing this differential together with other pulse counters was demonstrated at the Physical Society Exhibition[3] in April, 1955, maintaining motor speeds from 200 to 4 500 rev/min locked to a 10kc/s frequency standard.

Further Applications

Further development with the differential will be aimed at obtaining higher operating frequencies with new types of counting tube and reliability by using improved circuits and valves, although experience so far has been promising. Among other applications the circuit lends itself to the digital control of machine tools since the differential basically compares positions of shafts or slides rather than speed. If used in tool control it might be necessary to extend the differential by one or more reversible decades in order to store the count until the tool obeyed the command. This can be done by using the same type of drive circuit for each stage and handing on the count as the glow leaves cathode 9 for transfer electrode T_1 and subtracting a count as it leaves T_1 for 9. When first envisaged it was thought that two pentodes would have to be employed to recognize (using suitable integrating circuits to their suppressor grids) these two states. Recently a new Dekatron has been described[4] with the transfer electrodes between 9 and 0 separately brought out. If this tube becomes available in the form of a selector tube rather than a counter it will simplify the construction of such a simultaneous reversible bi-directional multi-decade counter. It should be noted that reference 4 deals with the special case of reversible counting of mechanically derived impulses where the two trains of transfer pulses can be obtained with the correct phase automatically: only one instruction is given to the counter at any one instant. A hard valve counter for this purpose has also been described[5].

Acknowledgments

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A patent application has been filed in connexion with the work carried out at the Mechanical Engineering Research Laboratory. The rights have been assigned to the National Research Development Corporation, 1 Tilney Street, London, W.1, who will be pleased to hear from anyone interested in making or using the digital differential for precise speed control or any other purpose.

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