Valve Reliability in Digital Calculating Machines

By L. Knight*, A.M.I.E.E.

This article discusses measures which can be taken to reduce the number of valve failures and to minimize the inconvenience caused by the remaining unprevented failures. Although these measures are considered primarily with regard to digital calculating machines many are applicable to other electronic equipment.

ONE of the most important problems associated with the design of digital electronic calculating machines is that of reliability. This is especially true now that such equipment is beginning to be used for accountancy where work must often be carried out to a rigid timetable and frequent interruptions for servicing cannot be tolerated.

The most common cause of breakdowns in electronic equipment is the valve and it is therefore this component which must receive most of the designer's attention. He must not concentrate solely on reducing the number of breakdowns due to valve failures but must remember that this is only one aspect of a wider problem, that of minimizing the inconvenience which valve failures cause to the user.

The procedure for tackling the problem would appear to be divisible into the following distinct steps:

(1) Choice of inherently reliable valve types.
(2) Measures to minimize valve deterioration.
(3) Designing the circuits to be as tolerant as possible to changes in valve characteristics.
(4) Testing valves before insertion into the machine.
(5) Comprehensive testing of the complete machine.
(6) Preventive maintenance in the field.
(7) Provision of facilities for dealing rapidly with any unprevented failures.

Choice of Valve Types

Considerable research into valve reliability is now being done by many valve manufacturers. When the improved types become readily available for industrial purposes they should prove valuable, even though most of the research at the moment does not appear to be directed at the same kind of reliability that is required in calculating machines. The main emphasis at present seems to be on valves which will operate reliably for 1 000 to 2 000 hours under extremes of ambient temperature, in equipment which may be subjected to rough mechanical treatment[1]. In a calculating machine the main requirement is for valves which will work for 20 000 hours or more in a stationary equipment, usually in a temperate climate.

Valves often vary very considerably from one manufacturing run to another and it is not very helpful to use large scale life-tests to determine which types and makes are the best. A life-test takes several years to conduct and at the end of that time the results cannot be taken as applicable to current production valves. Consequently it would seem that the designer of electronic apparatus must rely more on an understanding of the causes of valve failures and combine this with the experience of those who have used large quantities of valves in the past to predict which contemporary valves have the greatest potentialities for reliability and longevity.

One factor that must be borne in mind when choosing types is that valves are most reliable when manufactured in continuous and smooth-flowing production runs. It is wise, therefore, to avoid types which are only produced in small quantities or which are obsolescent and this suggests that the choice should fall on types from the popular range of miniature glass-based valves.

These valves, however, have some disadvantages. The contact between the pins and the valve holder is less reliable than with the octal base and sometimes gives rise to noise or intermittent failures. There is also the danger that, when the valve is inserted into the holder, stresses may be set up in the glass. These may not be evident immediately but may cause cracks to develop at a later date. In spite of the development of special techniques, which include the avoidance of stiff wiring to the valve holders and the use of wiring jigs, the situation does not appear to be completely satisfactory. Rowe[1], for example, claims that damage due to valve insertion alone jeopardizes the chance of obtaining a failure rate of less than 1 per cent per 1 000 hours.

The safest course seems to be the elimination of conventional valve holders altogether. The G.P.O. have found it advantageous in repeaters to spot-weld short flexible leads to the valve pins and then solder these wires into a special valve holder[2].

In other respects the reliability of miniature valves appears to be comparable with that of larger ones. The scaling down of the electrode assemblies has produced certain manufacturing difficulties and resulted in higher bulb temperatures, but these set-backs seem to have been successfully overcome. As regards invulnerability to physical shock and vibration, the miniature is generally better than the larger types.

Since one of the greatest causes of valve breakdown will be heater failures it is worth while to consider which valves can be expected to have the lowest heater mortality. It would seem that thick heaters tend to last longer than thin ones and that, because of this, a low voltage heater is preferable to a higher voltage one of the same power rating. On the ENIAC it was found that the failure rate of valves with folded heaters was considerably higher than that of those with twisted heaters[4]. Thus, for example, one would expect the ECC33, which has two 3·15V 0·4A spiralled heaters in series, to be better than most makes of 6SN7, which have two 6·3V 0·3A folded heaters in parallel.

Minimizing Valve Deterioration

Having selected valve types which seem to have the greatest potentialities for long life it is essential to ensure that these can be realized. It is advisable to operate all valves at very conservative ratings, to adhere to the standard code of practice[3] and particularly to any special recommendations of the manufacturer.

A lower heater voltage than the nominal one specified by the manufacturer will lengthen the life-expectation of

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the heater, but any cathode deterioration which may occur will then be far more pronounced. However, provided that the anode voltage is low, there may be some overall advantage in slightly under-running the heater. In the ENIAC, where anodes and screens are operated at about half their maximum continuous service voltage ratings and about a quarter their maximum current ratings, experiments tended to show that the optimum heater voltage for 6·3V valves lay somewhere between 6·0V and 6·3V[5].

It seems likely that heater failures will be reduced if it can be arranged to avoid the heavy heater current surge which normally occurs on switching on. This is admittedly only conjecture and tests on the ENIAC failed to prove that it gave any measurable advantage[4]. Nevertheless, it seems worth while to err on the cautious side and incorporate this feature. If voltage stabilization is used on the heater supply it will only require a minor modification to give a gradual initial voltage rise.

Another unconfirmed supposition is that it may be mildly injurious to the cathode to apply any anode or screen potentials before the heater has fully warmed up. Thus it may be beneficial to arrange for a delay of about two minutes on the H.T. supplies.

Wherever possible it should be arranged that if any fault occurs in the machine it does not have any disastrous repercussions in any other part of the machine. Obviously it is impossible to cover every contingency but it is essential, at least, to ensure that no widespread valve destruction can ensue from a failure in a master circuit or in a bias voltage supply.

Special attention should be paid to valve cooling. With the large number of valves usually found in calculating machines a forced air draught is desirable. To avoid complications with dust filters and to enable the internal temperature to be independent of the room temperature, it may even be advisable to have a completely enclosed air circulation system with its own refrigeration plant[6].

Tolerant Circuits

A large proportion of the valves will not have sudden catastrophic failures. Their life span will be the time taken for their characteristics to deteriorate to a level which prevents reliable operation in a given circuit. Thus in order to obtain a life of, say, 10 000 hours, circuits must be used which will accept the changes in valve characteristics occurring during that time. Before this can be done, some estimate must be made of what these changes will be.

With valves made for repeaters, Eaglesfield[7] has found that the deterioration is due mainly to the growth of resistance of the interface between the cathode core and the oxide coating. After rising to a certain value within the first few thousand hours this resistance has been found to remain essentially constant at a value given by the following formula:—

$$R \simeq \frac{40}{A_k} \simeq \frac{120}{W_h}$$

where R is the interface resistance in ohms,

A_k is the area of the cathode coating in sq.cm,

W_h is the rated heater power in watts.

Results of a valve life test conducted by the author have shown that with standard commercial valves a greater deterioration can sometimes occur. 80 type ECC33 double triodes, consisting of samples from several different deliveries, were run for 3 250 hours under conditions which simulated a typical circuit application. The majority showed little change in anode current during the period but with 14 of the 160 triode units there was a marked fall. Fig. 1 shows the histories of several of the worst of these. The curves show a tendency for the rate of deterioration to fall after several thousand hours and it seems reasonable to suppose that over a period of 5 000 hours at least, and possibly over 10 000 hours, few of the valves would have fallen much below the level of d. Subject to any future evidence to the contrary, this level has been taken as representative of the worst deterioration to be expected with ECC33 valves over a period of 10 000 hours.

The static characteristics of d after 3 250 hours were found to be similar to those of an average new triode unit with a resistance, R_k in series with the cathode and another R_a in series with the anode. It is presumed that R_k is a measure of the internal cathode resistance and that R_a, since it limits the maximum possible anode current, is indicative of a drop in cathode emission. The values of R_k and R_a were approximately 1 000 and 7 000Ω respectively.

In the Hollerith type 541 multiplier* it has been made a criterion for any circuit using an ECC33 that it must operate satisfactorily both with a valve artificially aged to this level and with a top-limit new one. Moreover, any circuit element, such as an Eccles-Jordan trigger, which uses a plurality of triode units must be capable of working satisfactorily with any combination of good and bad triodes.

Under dynamic conditions at high frequencies a genuine aged valve may not behave so badly as a synthesized one,

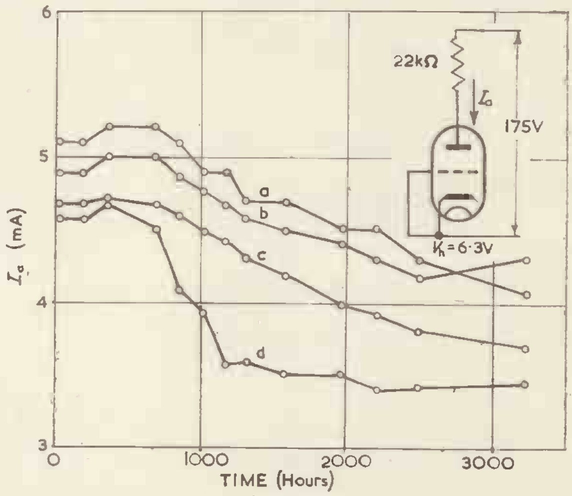

Fig. 1. Characteristics of several of the worst valves tested

The anode load was raised to 47kΩ between measurements to make the average anode current during the soak period approximate to that under equal mark-space ratio pulsed conditions.

due to the fact that the cathode interface resistance of the former will be shunted by a capacitance. This gives an added safety factor.

No comparable evidence has yet been obtained on what values of R_k and R_a to expect with any other valve types and tentatively it has been supposed that they will be related to the cathode area, and therefore to the heater power. A single ECC33 heater is rated at 1·26 watts and thus equivalent values for R_k and R_a for other valve types are estimated as below:—

$$R_k \simeq 1\,000 \times \frac{1{\cdot}26}{W_h} \simeq \frac{1\,300}{W_h} \text{ ohms}$$

$$R_k \simeq 7\,000 \times \frac{1{\cdot}26}{W_h} \simeq \frac{9\,000}{W_h} \text{ ohms}$$

In a pentode the screen current will also be restricted when the cathode emission fails. This can be simulated in an artificially aged pentode by a resistance in series with the screen, its value being such that it will limit the screen current by the same proportion as R_a limits the anode current.

** An electronic multiplier, capable of working in decimal or £.s.d. notation, which is one of the range of Hollerith punched card accountancy machines manufactured by the British Tabulating Machine Company Ltd.*

The above methods of determining the characteristics of aged valves must be taken as very approximate. They are based on rather meagre evidence and make certain questionable assumptions. Nevertheless, they give a limit which, while providing a generous latitude for deterioration, does not make circuit design unduly difficult.

The actual procedure for designing equipment to accept the required range of valve characteristics will depend on the circuits involved but the principles will be broadly as follows:

(a) To make each circuit element accept the widest possible variations of amplitude, shape and timing of the input pulses.

(b) Then to ensure that the output waveforms of each circuit element will be always within the limits required by the succeeding stages.

Normally in a digital machine a valve will only be used as a two state device. It will either be cut off or conducting, the grid in the latter state normally being clamped at the cathode potential by grid current. The input waveform, therefore, must traverse sufficiently negative to ensure that the grid is beyond the cut-off point and sufficiently positive to override the voltage drop across R_k. If two valves have their grids commoned, allowance must be made for the fact that the valves may have different values of R_k. Each grid should be connected through a resistance to prevent them both limiting at the same potential.

To ensure the minimum variation in the amplitude of the anode waveform the anode load should be as high as possible so as to swamp the effects of R_a and R_k. If necessary, the sharpness of the waveforms can be improved by the use of limiting diodes[6].

In certain instances, such as the "read" amplifiers in a magnetic drum store, valves may be used in class-A. Here the effects of deterioration can be minimized by the use of negative feedback. Even though this may necessitate the use of extra valves to obtain the required gain, it will probably result in fewer valve replacements.

In the circuit design, account must be taken of the fact that component values will deviate from the nominal figure and that any valve must give satisfactory results in spite of this. The fact that a component has a certain tolerance printed on it means that it was within those limits when tested at the time of manufacture. It does not necessarily mean that it will remain within those limits for a number of years, and an allowance must be made for the maximum anticipated drift. Even if cheaper components appear to be adequate it seems wise to err on the cautious side and use stable and close tolerance resistors and capacitors if they will give a greater margin for valve variations. In fact, it seems a sound principle that everything possible should be controlled to tight limits to allow the greatest safety margin for the most uncontrollable item—the valve. In line with this policy, the power supplies should all be stabilized, and the D.C. ones free of ripple.

The use of simple circuits is usually preferable. It is unwise to rely on characteristics which are not utilized in the normal applications of a valve. The manufacturer may not be controlling that characteristic and there may not be evidence available on what variations to expect. It is probably advisable even to avoid the use of pentodes. The variations of all the different electrode characteristics within their permitted tolerances, together with changes due to cathode deterioration, make it difficult to assess what variations in performance to expect. With a little ingenuity a pentode can often be replaced by a double triode and it would seem preferable to do this whenever possible.

One factor which should not be overlooked is the possibility of parasitic oscillations. If one side of an Eccles-Jordan trigger oscillates at a very high frequency the trigger may become monostable. A pulsed valve which oscillates can radiate to another, apparently unconnected, circuit where it may be rectified and produce a spurious pulse. Faults due to parasitic oscillations may occur sporadically as stray capacitances and inductances change and can be very baffling. It is infinitely preferable to avoid the possibility of such faults by making a strict practice of including stopper resistors in all control grid and suppressor grid leads. Long earth leads from the valve holders should also be avoided, especially when they are common to several electrodes.

Valve Testing

The only satisfactory type of valve reliability test seems to be a batch test, every valve in the batch being rejected if the performance of the batch as a whole is not satisfactory. Samples from the batch can then be tested to destruction. For such a test to be most useful the valves should be kept in the same batches as those in which they were manufactured. This, coupled with the economic consideration that vast numbers of valves may be rejected to effect the elimination of a few faulty ones, makes it rather impracticable as far as the user of valves is concerned.

Even though no quantitive measurement of reliability is possible it is still worth while to test each valve individually before insertion in the equipment.

The anode current can be measured under conditions which simulate the conducting state of the valve in the circuit in which it is to be used. Those valves with the lowest anode current can be rejected on the assumption that they are likely to reach the lowest acceptable limit sooner than the others. The choice of a test limit will be to some extent an economic one, dictated by what proportion of rejects can be tolerated. A reasonable test figure seems to be one which rejects about 5 per cent. This eliminates any which are exceptionally low without incurring a large wastage.

Another safeguard is to reject those valves with high reverse grid current, this being indicative that the gas pressure is high and that, in consequence, there is more danger of cathode poisoning. Here again the test limit will have to be determined on economic grounds.

Checks can also be made of other characteristics, such as the grid cut-off voltage, to ensure that they are within the required limit. There can be a mechanical inspection for any visible defects, such as loose electrode assemblies or hot spots on the heaters, which may impair reliability.

Testing of Complete Machine

Considerable attention must be paid to the test procedure of the complete machine. The tests must ensure that everything is working exactly as the designer intended and that there are not any faulty components enjoying the tolerances which he has meant as a safeguard for valve deterioration. An extensive check should be made to verify that the output waveforms of every stage are within the limits to be expected with new valves. It is also extremely desirable to check that each stage will tolerate the required variations in input waveforms. This latter test will only be practicable if the machine is constructed of small units which can be tested individually prior to their incorporation in the machine.

It is highly advisable to test every component. Even with the highest quality components there are occasional ones outside limits or wrongly marked and, although these should show up in a comprehensive functional test, it is safer, and often quicker in the long run, to have a 100 per cent test of all components. Often it is possible to do this when they are wired into sub-assemblies, in which case it will check that no damage has resulted from handling or soldering.

Care should be taken before switching on for the first time that there is no fault which may endanger the valves. Immediately after switching on it is a good plan to check that all the grid potentials are safe. Although any faults in this respect would be discovered eventually, this action prevents the possibility of any valves passing excessive current for any length of time.

In electronic equipment generally it has been found that a large proportion of the valve failures, especially catastrophic ones, occur during the first 250 hours. It is prudent, therefore, to make the testing include a soak run which is long enough to ensure that the valves have been running for this period before the machine is passed to the user.

Preventive Maintenance

Even if the utmost care has been taken in the design, production and testing of an electronic calculating machine there will inevitably be some valve failures. Precautions must be taken to prevent these causing any serious inconvenience to the user. It is extremely valuable, for example, to institute periodic checks to detect any valves whose characteristics are approaching the danger level. These valves can then be replaced before they actually cause any errors. The most obvious way to perform this check would be to remove each valve individually to test it. This would be extremely tedious and it is very likely, especially with glass-based valves, that it would introduce more faults than it prevented.

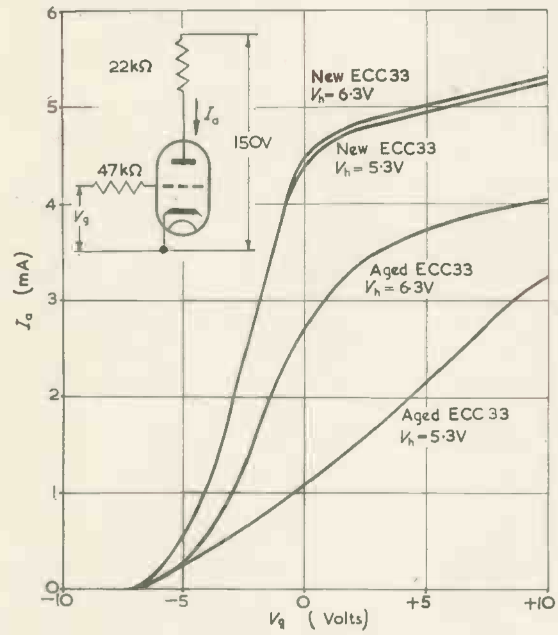

Fig. 2. Effect of heater voltage

The procedure which has been adopted with a number of computors is that of marginal checking. This usually involves putting the machine through a test run with one or more of the power supply voltages offset from their normal values and comparing its results with predetermined answers. Any valve which has deteriorated badly and has only been operating with a small safety margin will then cause an error which can be traced. On the ENIAC the pulse repetition frequency is raised for marginal checking[8].

If the marginal checking is made semi-automatic, as on the Whirlwind[9], it can be performed by the normal operator. The serviceman then need not be called in unless the result of the check is unsatisfactory.

An interesting point with regard to marginal checking is the effect of the heater voltage on the performance of a valve. If the valve has suffered no cathode deterioration there will be negligible change in its characteristics (with low anode voltages) if the heater voltage is lowered by 15 per cent. But if there has been deterioration this will become much more apparent as the heater voltage is lowered. Fig. 2 shows this effect in a typical application. It is supposed that an ECC33 is to be used with a 22kΩ anode load and an effective grid circuit resistance of 47kΩ. Assuming that in the conducting state V_g will be +5V, a typical new valve will pass 5mA and a badly aged one (d of Fig. 1) will only pass 3·7mA. If this latter figure is near the danger point the valve will fail when the heater voltage is reduced to 5·3V and the anode current falls to 2·1mA.

Facilities for Rapid Servicing

Not all valve failures will result from progressive deterioration and measures must also be taken to deal with unpredictable failures. The first requirement is that any fault should be discovered as soon as possible and the best way of ensuring this is to incorporate some form of self-checking. Often this can be done by arranging that the machine automatically performs every calculation by two different methods and compares the two results. With complex computors this is not always possible and some other system must be devised. In the S.D.C. Raytheon computor[10], for example, each number has associated with it a check number which is the weighted sum of the binary digits. These check numbers are used to verify arithmetic operations and also to check that numbers do not suffer any mutilation in transfers or in storage. In the UNIVAC[11] the binary code for each character (which may be a decimal digit) contains a check digit which is chosen to make the sum of that group of digits odd. During all transfers each character is examined to check that the sum of the digits is still odd. Periodically every character in the acoustic delay line storage is also examined. Arithmetic operations are checked by performing them simultaneously in twin arithmetic units which check against each other.

There must also be a service engineer within easy reach and facilities for him to diagnose the fault easily. Neon indicators can be included in the machine to give a visual display of the contents of valve registers. They can even be used to indicate short-circuit capacitors and open-circuit resistors. It may prove worthwhile to build an oscilloscope into the machine. If the machine does not use a dynamic storage medium it is a great advantage to have facilities for pulse by pulse operation at low speed.

An engineer who is thoroughly acquainted with the functioning of the machine can often diagnose a fault very quickly from the nature of the errors it causes and it is extremely helpful to have a series of test problems especially prepared for this purpose. This method of fault-finding is invaluable for intermittent faults.

There must also be provision for the engineer to rectify faults quickly. The machine should be made of easily replaceable units of as few different types as possible. The engineer then need not isolate the precise fault but only narrow it down to the faulty unit and replace this.

In many cases it will be preferable to have several small identical calculating machines sharing a job rather than one large machine doing it unassisted. A fault then will not immobilize the whole installation, but only one unit, and it will still be possible to continue at reduced speed.

Valve Failure Figures

Most of the measures outlined above were adopted with the Hollerith type 541 multiplier. Miniature valves were not used, however, because at the time of the conception of this machine their suitability for calculating equipment was not felt to be sufficiently well proved. The two main types employed were the ECC33 double triode and the 6F32 short suppressor base pentode, both octal based valves. The original valve testing and maintenance techniques were not as thorough as outlined above.

None of the multipliers has been in service long enough yet for any extensive evidence on valve failures to be obtained but the failure rate to date, excluding the 250 hour soak period, has been less than 1 per cent per 1 000 hours. With only a small number of failures it is impossible to draw any definite conclusions, but there is an inference that the ECC33 is more reliable than the 6F32. On later versions of the multiplier where valve failure prevention is being tackled more strictly in accord with this article it appears probable that the failure rate will be less than ½ per cent per 1 000 hours.

In the Manchester University computor the valve failure rate has been approximately 1 per cent per 1 000 hours over a period of more than 5 000 hours[6]. It is interesting to note that 180 out of the 239 valve failures during this time were due either to low emission or faulty valve bases. This suggests that could these two faults have been eliminated the valve failure rate on this machine would also have been less than ½ per cent per 1 000 hours.

It would appear from the evidence of these two machines that, even with standard commercial valves, it should be possible to obtain a valve failure rate of ½ per cent per 1 000 hours for the first few thousand hours. If failures continue at this rate indefinitely the average valve life would be 200 000 hours, that is to say, about 100 years if run for 40 hours a week. It seems presumptious to expect this to be achieved and it must be concluded, therefore, that after a time the failure rate will increase. Experience may prove it expedient to withdraw a machine from service when the failure rate exceeds a certain level and replace all the valves.

Conclusion

Summarizing, it would seem that the problem of valve failure involves the consideration of a variety of widely different factors. Although the greatest onus for valve reliability falls on the valve manufacturer, it would appear possible for the designer of electronic calculating equipment to achieve, for the first few thousand hours at least, a valve failure rate of less than ½ per cent per 1 000 hours.

Having reduced the number of failures to a minimum there are still other important measures which can be taken to reduce the inconvenience caused by the remaining unprevented failures. Although this article has been confined to valves it is worth noting that some of these measures apply equally well to failures due to other causes.

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AN AMPLIFIED-TORQUE CLUTCH

By R. Voles*

The device described gives an approximately linear control of large torques at slow speeds. The torque is provided in the first place by a magnetically-actuated plate clutch. This torque is then amplified by means of a torque amplifier of the tape type.

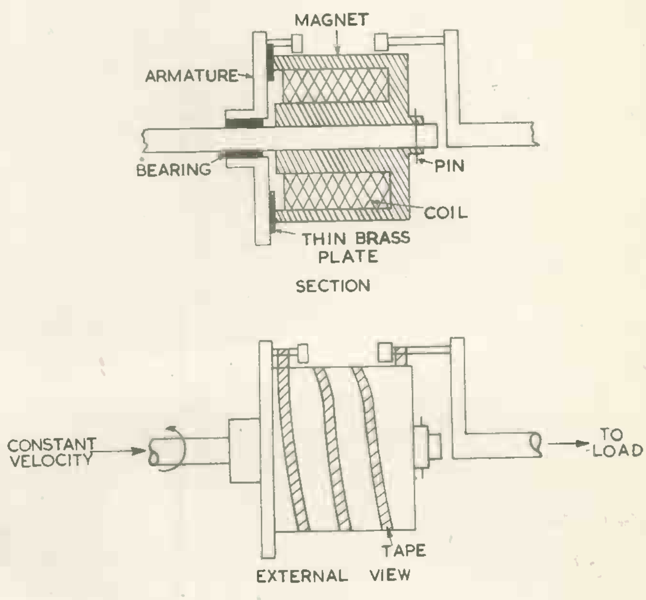
The primary torque produced is that required to cause slip between a flat-faced armature and a "pot" electromagnet which is rotated at constant velocity. The magnet is mounted on the driving shaft, and the armature is mechanically free to move on a bearing along the same shaft when the magnet is energized. The magnet current is conveyed to the coil through slip rings and control of the current gives an approximately linear control of the torque, which is therefore virtually independent of slip speed. A thin non-magnetic sheet is fixed to the face of the armature to reduce the effects of remanance.

In the torque amplifier the tape is wound around the cylindrical outer surface of the magnet. The tape is pinned to a point on the circumference of the armature, passed around the surface of the magnet the requisite number of times and fixed to a crank on the load shaft which is coaxial with the magnet and the driving shaft.

The primary torque and the torque amplifier are both unidirectional; for servo purposes, therefore, it is necessary to use two clutches driven in opposite senses. This arrangement has the added advantage that small constant currents may be maintained in the magnet coils to ensure that the tapes are permanently taut.

The chief advantage claimed for this method over one in which the tape amplifier is controlled by a torque motor is a reduction in size and complexity. Also, unless two torque motors are used, the unit cannot be split into two halves and situated conveniently in the equipment. Another advantage is that the device automatically takes up any movement which might be caused by a variation in tape length.

Cross section and external view of the clutch.



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