Digital Speed Control Servo

by C. W. Ross,* *M.I.E.R.E.*

A d.c. motor control system is described which uses a retriggerable monostable pulse as a reference source. The period of a tachometer is compared with the monostable pulse in a simple high-gain pulse-width discriminator driving the motor control elements. The servo system is shown applied to a high performance 2in magnetic tape transport where better than 0.1% speed accuracy is required.

Before going on to the circuit description, it is necessary to mention the tachometer used in the design, as this has some bearing on the techniques used in the electronic section of the unit.

Recent advances in flexible-magnet technology contribute to reducing the cost of the electromagnetic a.c. tachometer illustrated in Fig.1. The rotor is a disc of 0.06 inches thick flexible magnetic sheet, magnetized with 64 poles. The stator is a single-sided printed circuit board bearing the winding pattern. Fig.2 shows the magnetic pattern of the rotor seen by means of a magnetic particle viewer. The rotor was magnetized on a jig referenced to the centre hole, the magnetic pattern being produced by a multiple-pole electromagnet driven by an s.c.r. and capacitor discharge circuit. The rotor disc is cemented to a rigid metal backplate so that the assembly can rotate with the motor shaft. The stator is positioned approximately 0.02 inches from the rotor and is rigidly fixed to the motor housing.

The output voltage is sinusoidal and the frequency is proportional to velocity. The prototype gave 40mV r.m.s. per 1000 r.p.m., with a source impedance of less than 1 ohm at 1kHz. Amplitude is proportional to frequency, following a 6dB/octave slope, and is affected by spacing between magnet and pickup.

Fig.3 shows the complete assembly attached to the motor. Adjustment is provided to minimize alignment error of the stator by checking the flutter of the complete system with the tachometer frequency conveniently adjusted to 3kHz, the centre carrier frequency for most flutter-measuring instruments. Typically, the flutter is below 0.01% r.m.s. using a 0.5 Hz - 200 Hz bandwidth.

Servo

The trend in speed control systems seems to be toward digital techniques, rather than the well-established linear methods of operation.

Consider the basic block diagram in Fig. 4. The alternating signal from the tachometer is amplified and amplitude limited by a differential operational amplifier A_1. The output drives a precision monostable multivibrator that generates a pulse at each positive-going transition of the signal from amplifier A_1. The complementary output of the monostable circuit is used to drive a pulse-width discriminator circuit, in which the charge and discharge rate of the capacitor is controlled by resistors R_1 and R_2, respectively. As the tachometer frequency increases, the period of one cycle of tachometer signal will approach that of the monostable circuit. The monostable produces a progressively narrower pulse, because its complementary output is the *difference* between the uniform "normal" pulse and the period of the tachometer. If the tachometer continues to increase frequency, its period will equal that of the monostable and the complementary pulse will suddenly disappear. The pulse width discriminator circuit senses this rapid change and the charge potential on the capacitor C falls. The potential change across this capacitor is amplified by a high gain d.c. servo amplifier which controls

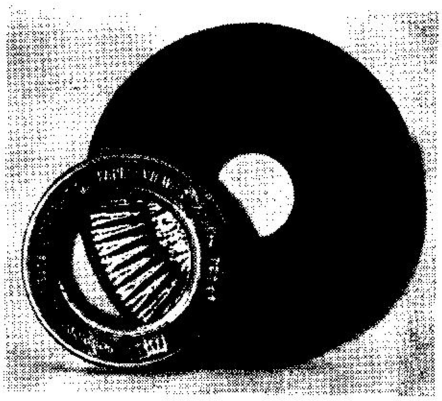

Fig. 2. The magnetic pattern on the rotor, made visible by a particle viewer.

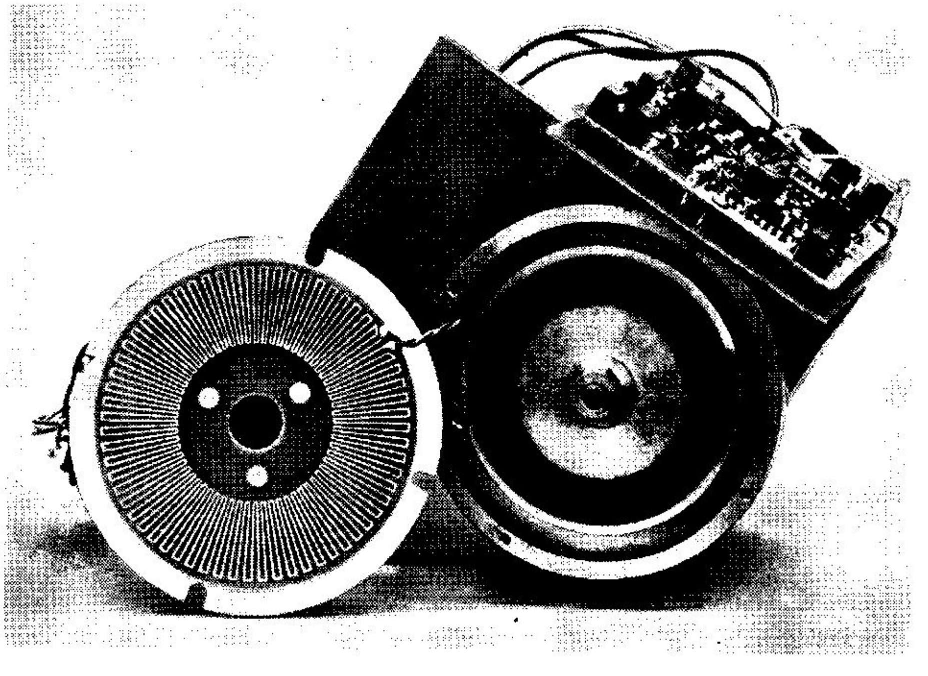

Fig. 1. Tachogenerator, showing the printed-circuit stator winding and the flexible magnetic rotor.

3M Company, Camarillo, California.

the motor. The output of the d.c. power amplifier has complementary transistors connected to enable one transistor to act as a brake; the other is used as the accelerator.

Reviewing this simple system, it can be seen that considerable drift-free gain is available by using the pulse width discriminator driven by the monostable complementary output. Stability and damping are dependent on the *RC* networks, and the phase lag and/or lead characteristics within the loop.

Electronic design

Tachometer amplifier. A μA739 dual operational amplifier was used for the tachometer amplifier and d.c. driver amplifier. This is available in a dual in-line package, providing high open-loop gain and differential inputs. An *RC* network was used to limit the current and voltage output, and to interface it with a 5V logic circuit. The complete servo circuit diagram is shown in Fig.5.

A step-up transformer was used, utilizing the very low impedance of the tachometer to make a larger signal available at the input of the amplifier. The differential inputs are driven push-pull, affording full gain of the i.c. and high common-mode rejection. From very low speeds upwards, the output from the amplifier is a square wave. Only the positive-going edges are used for control purposes, as the particular application for the servo did not warrant use of each zero crossing, which would have added complexity and mark-space adjustment requirements to the design. The design speed range was 600-4800 r.p.m., and half-wave detection (positive-going zero crossings) is adequate.

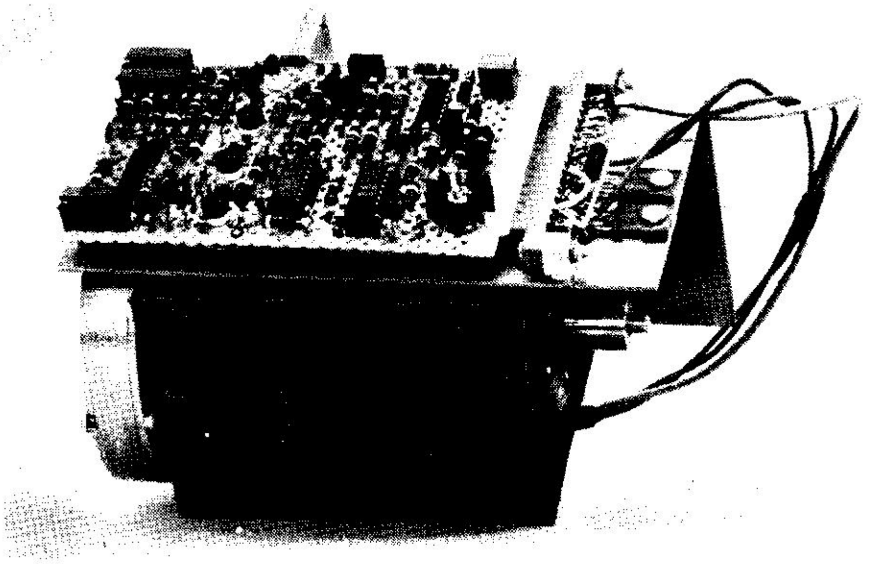

Fig. 3. Complete assembly of motor, tacho and electronic unit.

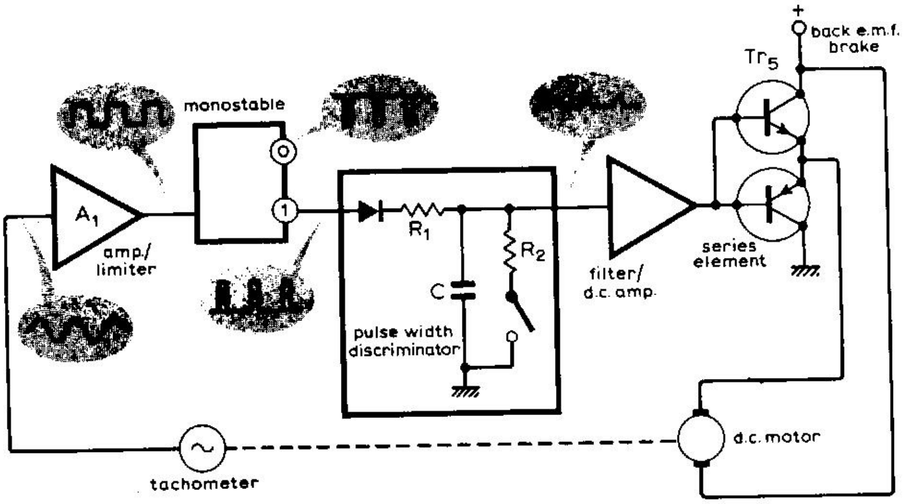

Fig. 4. System block diagram.

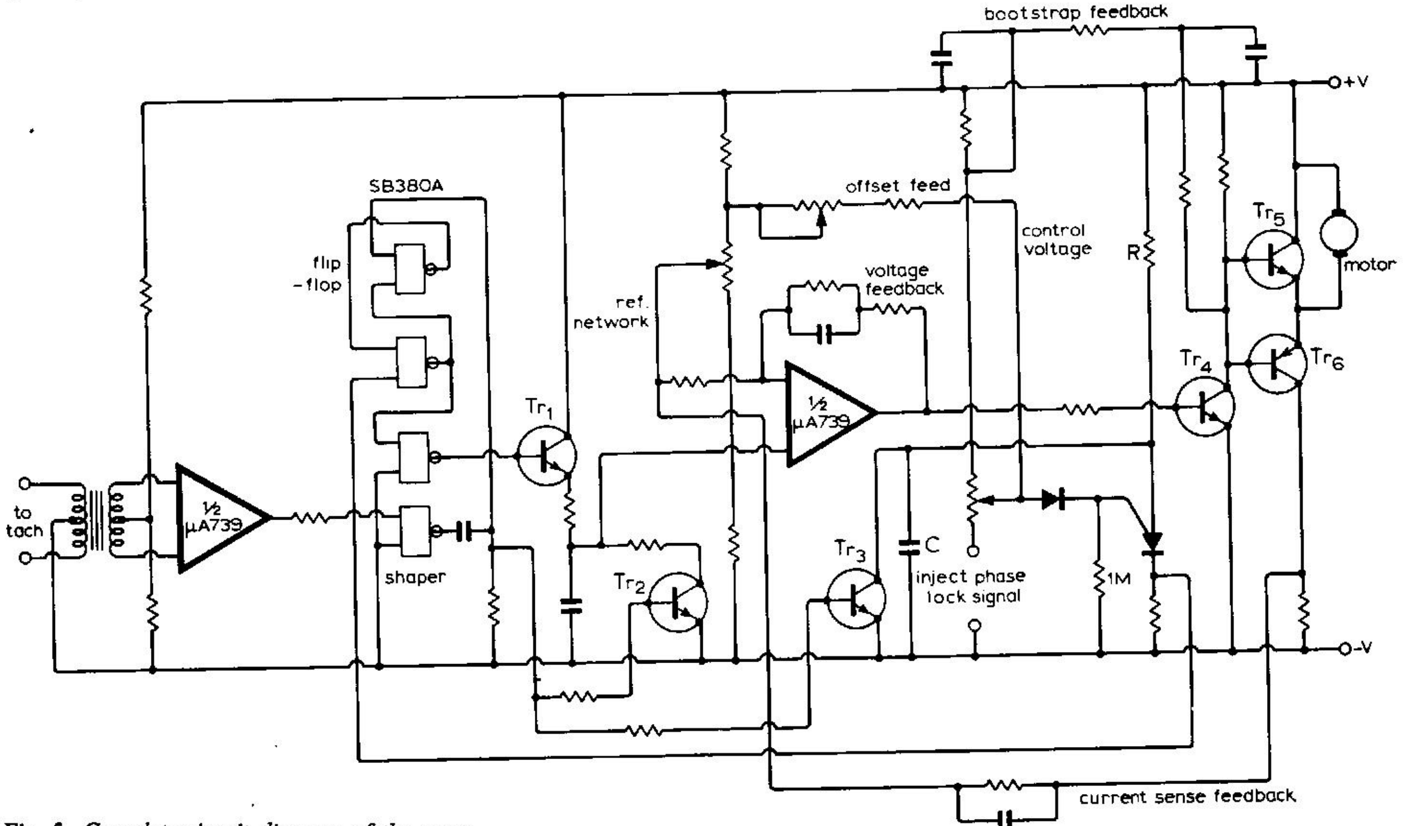

Fig. 5. Complete circuit diagram of the servo.

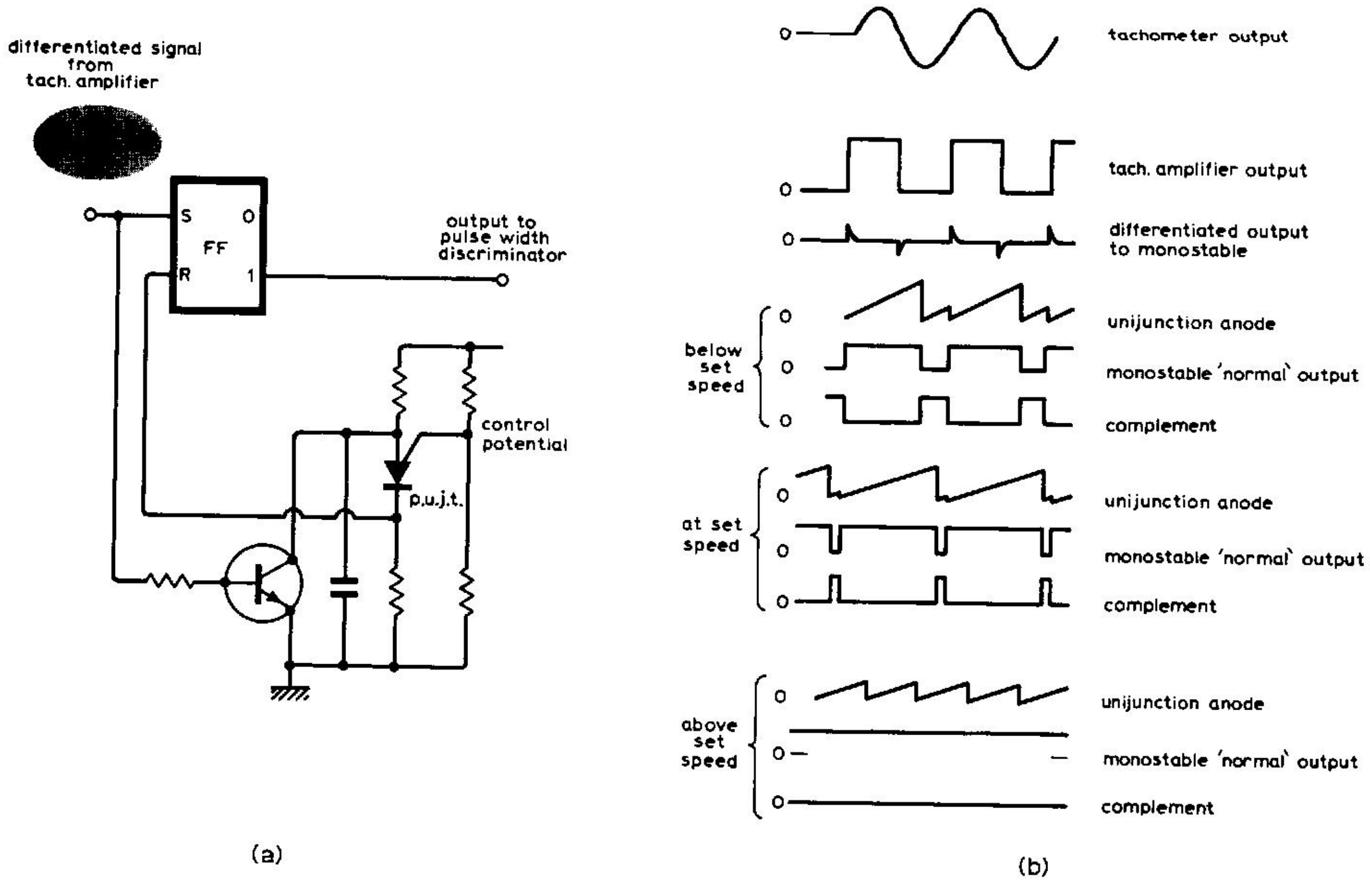

Fig. 6. (a) monostable and control circuit (b) waveforms in the control circuit.

Retriggerable monostable. In the original prototype circuit a 9608 monostable integrated circuit worked well, giving the necessary retriggerable characteristic to enable the 97% or more duty cycle to be achieved. However, temperature stability was found to be a problem when extreme accuracy is required. To overcome temperature stability problems, a lower cost, highly stable circuit was developed. This consists of a quad 2-input gate, interconnected as an R-S flip-flop, and a shaper circuit. The accurate timing pulse is derived from a programmable unijunction transistor, with a switching transistor added to reset the circuit in addition to its self resetting ability when the unijunction fires.

To explain the pulse generation sequence, reference must be made to Fig. 6(a) and (b). Directly upon the application of power, the R-S flip-flop can assume one of its two states. The unijunction timing capacitor charges, and the device avalanches to its negative resistance state, producing a sharp voltage pulse at the cathode resistor. This pulse resets the flip-flop if the set state came up. During this initial period where the tachometer signal is absent, the unijunction operates as a conventional relaxation oscillator. The reset state of the flip-flop is detected as a steady state signal by the pulse width discriminator and the motor accelerates under full power.

The flip-flop is also driven by the positive transitions of the tachometer signal, "setting" the flip-flop at each transition. At speeds below the controlled state, the flip-flop is continuously reset by the unijunction circuit after a precise delay period (determined by the *RC* network of the u.j.t. circuit). Notice that the timing capacitor is deliberately discharged by a transistor switch at each positive transition of the tachometer signal; this transistor is driven from the shaper section of the SP380A i.c. The waveforms appearing at various points of the system are shown in Fig.6(b) for three conditions.

The need for the transistor switch to discharge the timing capacitor, in addition to the natural function of the unijunction, will become obvious if the overspeed condition is examined. The capacitor potential is never allowed to reach the peak voltage point of the unijunction at overspeed, and the control voltage to the d.c. power amplifier is zero. This only occurs when an instantaneous command signal is given to slew to a lower speed, or to stop. At control speed, the pulse width from the monostable section of the servo is in the region of a few microseconds to about 15μs, depending on the stability criteria dictated by the friction, inertia, and compliance of the mechanical loads imposed on the system. The narrow pulses are sufficient to maintain partial charge on the pulse width discriminator capacitor, and the motor power is controlled at the level required to hold the speed selected.

Pulse width discriminator. The pulse width discriminator design is shown in Fig.7. This circuit uses Tr_1 to partially discharge capacitor *C* after the pulse has charged *C* to peak value. The discharge transistor is driven via the differentiating network, using the same pulses that drive the

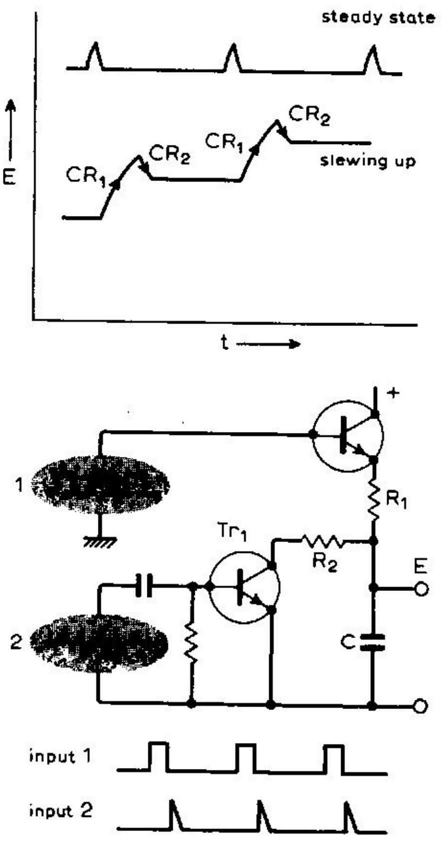

Fig. 7. Pulse-width discriminator, with waveforms.

monostable, hence the time displacement.

The object in this development was to produce a circuit that provided efficient conversion and low, easily filtered ripple content. Ripple can appear as a large portion of the motor current causing a.c. fields around the motor and audible noise at the tachometer frequency, both undesirable when the drive system is used in a magnetic tape transport.

The bandwidth of the servo is dependent on many things: the magnitude of the charge and discharge increments, the pulse width, the value of the capacitor C in Fig.4, and the reference voltage presented to one input of the d.c. amplifier. It was found that this reference voltage required adjustment for each speed, because the average value of capacitor C potential changed with variation of pulse repetition frequency when the optimum pulse width was found. The width of the pulse determines the closed-loop gain of the system, and further d.c. feedback was injected into the reference networks (Fig.5) so that optimum pulse width was obtained over the whole speed range using feedback derived from the main control voltage network. Good tracking was maintained over the required speed range. Measurements made on the pulse width discriminator used in the system illustrated in Fig.5 showed that a $1\mu s$ increment in pulse width produced 0.6 amp d.c. change in the motor circuit, which is ample gain to maintain efficient control.

Power amplifier. The d.c. power amplifier section shown in Fig.5 uses the other half of the μA739 operational amplifier, driving an output stage. One input of the μA739 is supplied from a d.c. potential divider; the other input is taken from the pulse width discriminator output filter. The resulting differential is amplified so that a large direct current level is available to energize the motor. Current feedback is obtained by a low value resistor effectively in series with the motor; the resulting voltage is fed back to one input of the preceding μA739 amplifier, reducing the overall gain to a convenient value. Another two feedback paths are used, one being conventional negative feedback and the other a reference tracking voltage derived from the p.u.t. gate control potential. This offset voltage ensures optimum control pulse width over the complete speed range.

Two output transistors are used, in complementary symmetry configuration. The p-n-p transistor controls the motor drive current, while the n-p-n does the braking when slewing to a lower speed or to a stop, using the back e.m.f. of the motor.

Performance

Accuracy. The speed accuracy was, as expected, proportional to the tachometer frequency and directly related to the tachometer pulse width feeding the peak detection network. To maintain the closed loop gain at a high value, a low impedance supply was necessary to supply the conventional permanent magnet motor rated at 12 in. oz. continuous torque output.

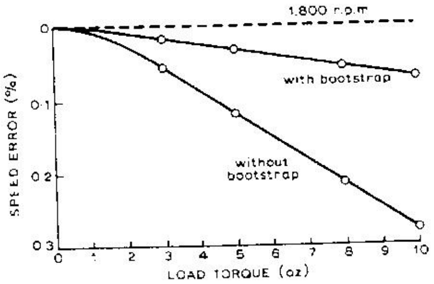

Fig. 8. Speed regulation curve of the system, with and without the bootstrap feedback circuit.

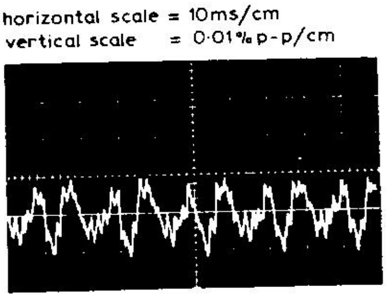

Fig. 9. Residual flutter of the system, showing a fundamental at 50Hz.

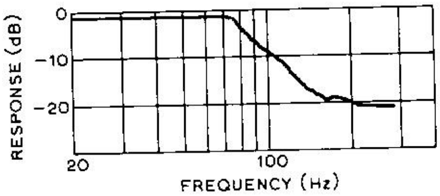

Fig. 10. Bandwidth of the servo only.

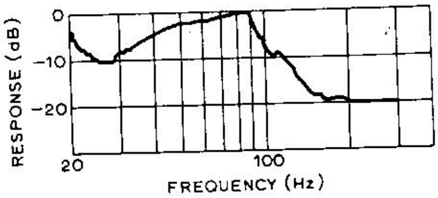

Fig. 11. Bandwidth of the system, showing the effect of compliance and mass of the drive.

Fig. 12. Response of the system to a 5Hz square wave injected into the control network.

The speed regulation comparisons are shown in Fig.8 for a midrange speed value. Improvement in speed regulation was achieved by using a d.c. "bootstrap" connection from the collector of the driver transistor Tr_4 in the d.c. amplifier section to the gate control network of the unijunction transistor in Fig. 5. The family of curves shown were obtained by checking speed regulation with and without the "bootstrap" connected.

Bandwidth and transient response. The ability of the servo to follow a sinusoidal speed variation by means of injecting a low frequency signal into the network controlling the p.u.t. timing is a measure of the system bandwidth, or response to a rapidly changing "instruction".

To measure the actual speed fluctuations of the servo, a flutter meter with a centre carrier frequency of 3000Hz was used to monitor the tachometer signal. The servo speed was adjusted to give a 3000Hz signal and the resulting flutter was measured, first without the sinusoidal programme, then with it. The frequency was varied from a few Hz to over 100Hz until the magnitude of the sinusoidal flutter component reduced by 3 dB. The residual flutter of the system alone is shown in Fig.9, which is typical for this design. The bandwidth graph is shown in Fig.10. Transient response was also measured in a similar way, by injecting a low frequency square wave into the control network. The resulting response waveform was displayed on a cathode ray oscillograph, and is shown in Fig.12 demonstrating the inherent near critical damping of this servo system. The response to a 1% step increment of speed was achieved in less than one revolution. The bandwidth of the servo was such that no ill effects were produced by the natural mechanical resonance of the motor shaft and tachometer motor assembly, as the resonance was above 850Hz.

When the motor was coupled to a typical tape transport using a Mylar belt and flywheel arrangement, a new set of conditions became apparent. The flywheel mass and the belt compliance form a resonant circuit of a significant Q value. Should the "gain" of the servo be high, oscillation can occur within the passband of the system, and adjustment of control pulse width ("gain") is required to give optimum stability. The action is analogous to the electronic a.c. amplifier when there is a resonant circuit within the feedback loop. Provided that the gain and phase shift are present, oscillation will commence (if they are present in excess of the classical requirements for stability). At first sight the belt and flywheel of the servo coupling drive is outside the "velocity loop", but it does feedback heavily, using the motor as a transducer to upset the control ability of the device. This results in the modified bandwidth plot of Fig.11.

Application. The reason for developing this particular servo was to incorporate it in a precision tape transport, to replace an a.c. two-speed hysteresis synchronous motor. The 3M professional 16-track recorder was used as a particularly good example to evaluate the servo drive, the two-inch tape producing a high load, and the differential "Isoloop" capstan extremely low wow and flutter performance over a bandwidth of 0.5-200Hz. The servo drive was shown to perform well, giving reliable low flutter performance figures of around 0.035% r.m.s. at 15 inches per second. Long-term speed stability and variations due to load change were found to be better than 0.1%.

The main sources of temperature drift are the base-emitter and saturation potential variations in Tr_1 and Tr_2 (Fig.5). The p.u.t. is compensated by the diode in series with the gate. The variations in Tr_1 and Tr_2 are complementary and tend to cancel as do the p.u.t. gate and diode combination. Typical spread on a pilot run of printed circuit units was ±0.2% speed variations for 0°C to 55°C temperature range. The actual environment seen in studio recorders is likely to be + 20°C to + 40°C. Some drift is also present during "warm-up" due to self-heating of the various components of the servo, but these effects were consistently below 0.1%.

The speed could be continuously varied over a 16:1 range, or switched to set values between 300 and 4800 r.p.m. A single resistor value can control the speed. The gate voltage of the programmable u.t. is the parameter which controls the speed — low voltage at this point produces shorter timing pulses from the hybrid monostable circuit, high voltage produces long pulses, and the servo will run at a speed where the pulse duration corresponds to the period of the tachometer. The limiting factor here is the extremes of voltage at the gate of the p.u.t. — the device has a low limit of a few volts, the upper limit being a potential few volts below the maximum rating for the device itself.

Another important requirement for range of control is the motor rating. At the high end of the range, there must be a good margin of potential left for the servo circuit to use and to provide effective control. The electromagnetic tachometer output must be high enough at the extreme low end of the speed range to produce the correct limiting action from the tachometer amplifier.

The servo could be phase locked to a sinusoidal signal within 2% of the tachometer frequency. The servo was mildly sensitive to amplitude of the synchronizing signal, the optimum point being about 0.5V r.m.s. injected into the lower end of the control network. This limited capture range is inherent in this type of integrated pulse system, allowing only one pulse to be generated by the monostable per period of tachometer, for satisfactory operation.

The author wishes to thank the 3M Company for giving permission to publish this paper, and credit is due to the engineers of the Mincom Division; Jack Mullin, Pete Amass, Ken Clunis, and others in the Audio Lab for their help and ideas during the development and in the preparation of this paper.

Further reading

Servomechanism Practice, Ahrendt and Savant, McGraw-Hill
General Electric Application Note 90.70
Motorola Application Note AN-445

Appendix

Electrical gain motor-to-tachometer	=64 rad/rad
Electrical gain motor-to-tape	=2880 rad/rad
Discriminator gain	=0.053V/rad
Voltage amplifier gain	=16V/volt
Power amplifier gain	=17.7A/volt
Inertia of motor and tachometer	=0.006 oz in/sec^2
Bandwidth, basic servo only	=100 Hz
Bandwidth, total drive system	=90 Hz
Residual flutter of tachometer	=0.01% r.m.s.
Residual flutter from tape	=0.035% r.m.s.
Residual carrier leakage current	=0.07A p-p
Residual rotational errors	=0.05A p-p
No-load direct current	=0.33A
Typical operating system current	=0.7A
On-off slew rate — up, basic servo	=4000 rad/sec^2
On-off slew rate — down, basic servo	=800 rad/sec^2
Incremental slew rate, up	=270 rad/sec^2
Incremental slew rate, down	=113 rad/sec^2
Long-term speed accuracy at 25°C	=0.1%
Temperature coefficient	=0.01% per °C
Signal-to-noise ratio r.m.s. ripple/max. drive current	=34dB
Flutter rejection coefficient $\frac{\text{open-loop gain}}{\text{closed-loop gain}}$	=55dB

Obituary

G. G. Gouriet

The early death of Geoffrey Gouriet at the age of 57 is a great loss, not only to his colleagues in the B.B.C., but also to his many friends and associates.

After various jobs as a clerk, service engineer and design and research engineer, he joined the B.B.C. in 1937 as a junior maintenance engineer. He was soon transferred to the medium-wave transmitting station at Penmon in Anglesey, and there spent all his spare time in studying the fundamental aspects of radio and electronic engineering. Most young people aspiring to the heights of an engineering career need a university training or the equivalent, but Mr Gouriet was quite capable of thinking for himself and this contributed to his great capacity for original work — he was the author of 31 patents and he wrote a considerable number of scientific and engineering papers. In 1939 he transferred to the crystal drive section of the B.B.C.'s transmitter department at the research premises in Balham, where his work had a major influence on the success of the method of operating several transmitters on exactly the same wavelength, thus enabling broadcasting to continue during air raids whilst preventing enemy aircraft from using the broadcast signals for direction finding.

In 1943 Mr Gouriet joined the research department, at first in the aerial section and then in television where he became Head in 1950. From that time until, in 1958, he resigned from the B.B.C. to become technical director of Wayne Kerr Laboratories, he made great contributions to the science of television. The method of equalizing the linear distortions imposed upon a television signal by the apparatus through which it passes, by means of a set of time derivatives of the signal was perhaps his most important technical contribution and although the method had been used in certain specific cases, he clarified and generalized the theory, making it available to all. In 1956 he represented the B.B.C. on the International Radio Consultative Committee of the International Telecommunication Union in the U.S.S.R. and Poland.

At Wayne Kerr he maintained his interest in derivative equalization and applied his ideas to the clarification and improvement of certain aspects of feedback and control theory, particularly as they concerned the rapid but precise movement of heavy mechanical equipment.

In 1964, Mr Gouriet rejoined the B.B.C. as head of research, bringing to this work his special gifts of enthusiasm, friendliness, technical integrity and an intuitive but incisive mind. In 1968 he became chief engineer, Research & Development; as overall chief of the research and designs departments. He had been elected chairman of the Electronics Division of The Institution of Electrical Engineers in 1964 and became a member of the Council of that institution in 1967. In 1968 he was chairman of Council of The Royal Television Society; in 1955 he had delivered the Fleming Memorial Lecture of that society. The climax of his career was the delivery of the Christmas Lectures of The Royal Institution in 1972. Shortly after this he was awarded the C.B.E., appointed as Visiting Professor of Electrical Engineering at Imperial College of Science & Technology with effect from 1st October 1973, and was elected to membership of The Athenaeum. He was a very gentle man whose enthusiasm and desire for deep understanding of natural philosophy inspired all who came into contact with him.