GENERAL DESCRIPTION OF ES130 SERVO SYSTEM.

Introduction.

The ES130 is a general purpose instructional D.C. servo system. The design makes the system very versatile and care has been taken so that as well as demonstrating principles the system can also be used for quantitative experiments which will give substantial agreement between theory and experiment.

The system versatility arises from a number of facilities in addition to the basic servo system. Such facilities are :-

An operational amplifier together with appropriate components for compensation networks.

The output system contains adjustable backlash and also a compliance-inertia resonance.

The input potentiometer can be rotated continuously by a small independent drive motor to enable closed loop steady state following characteristics to be investigated.

The internal ±300V stabilised supplies can be used externally to operate any associated units.

There is a monitor meter for general use.

The system comprises two units, a Control Unit (SC125), and a Servo Assembly (SA135), which are mounted in a single case. The Servo Assembly is in the lower portion and can slide out on runners for adjustments such as backlash, etc. The general layout is shown in Fig. 1a, both units having clear graphic panels to ease experimental work.

Servo Assembly (SA135).

This is housed in a tray in the lower portion of the case and slides forward on runners when two side fixings are released. The left hand rear portion of the tray contains the power supplies for the error channel and output display potentiometer, and for the input drive motor. In front of these supplies are the input drive motor and gear box coupled to the rear of the input potentiometer which can be rotated manually as well as being driven by the motor.

The error channel potentiometers are mounted close to the front panel, and are precision continuous rotation 12 tap potentiometers with an additional track on the output potentiometer from which a direct display of output position may be obtained. The right hand side of the tray carries the servo output system.

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Electrical Details.

The input drive motor control is at the left of the panel, and the input shaft can be driven up to about 2 r.p.s. Both input and output dials contain stroboscopic tracks to indicate 1 r.p.s. either 50 Hz or 60 Hz illumination. The sliders of the input potentiometer are energised with a nominal 50V D.C. supply and the supply polarity can be reversed by S_1. This is useful to maintain 0° - 0° alignment if 180° change is introduced in the forward path due to the operational amplifier. The sliders on the input potentiometer are aligned with the index arrow on the dial as shown on the panel diagram. Input and output potentiometers are interconnected at the 12 tapping points and two taps 180° apart are brought out to sockets (2), (3), which enable various test signals to be obtained by appropriate setting of the input potentiometer.

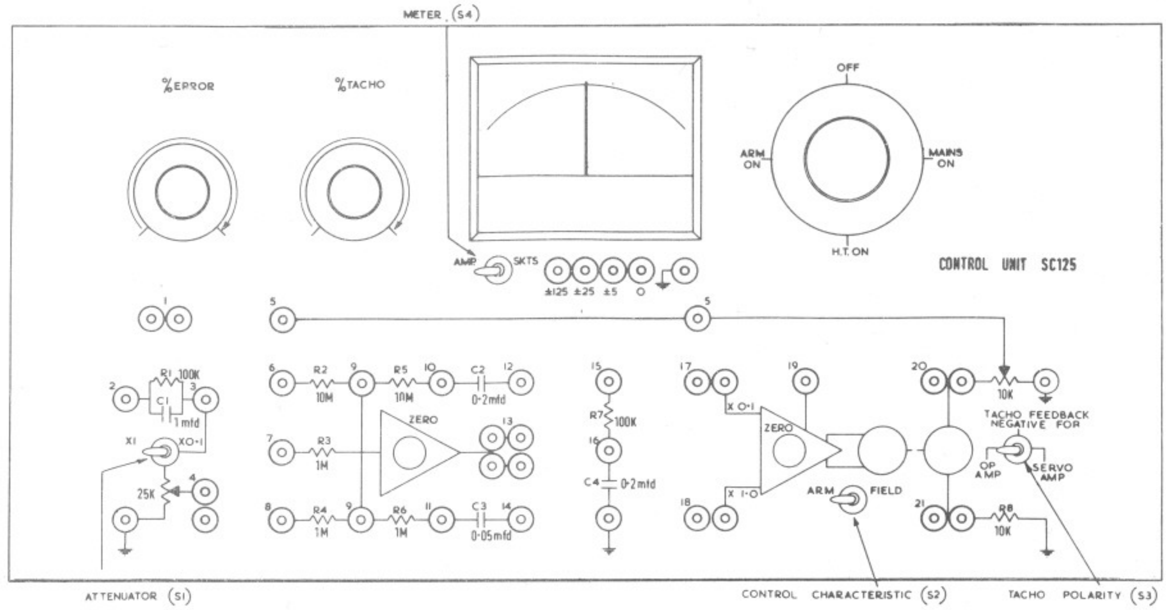
In operation an "error signal" is obtained between the sliders of the output potentiometer, sockets (4), (5), this signal being zero when the output sliders are at 90° to the input sliders. For this reason the index arrow on the output dial is set at 90° to the sliders. For normal use as an error channel, socket (4) is linked to (1) which gives a direct connection to the control unit panel, and (5) is earthed. A test signal can be introduced between (5) and earth from any suitable signal generator with a low impedance output and without supply ripple on the signal (Feedback TWG200 or 300).

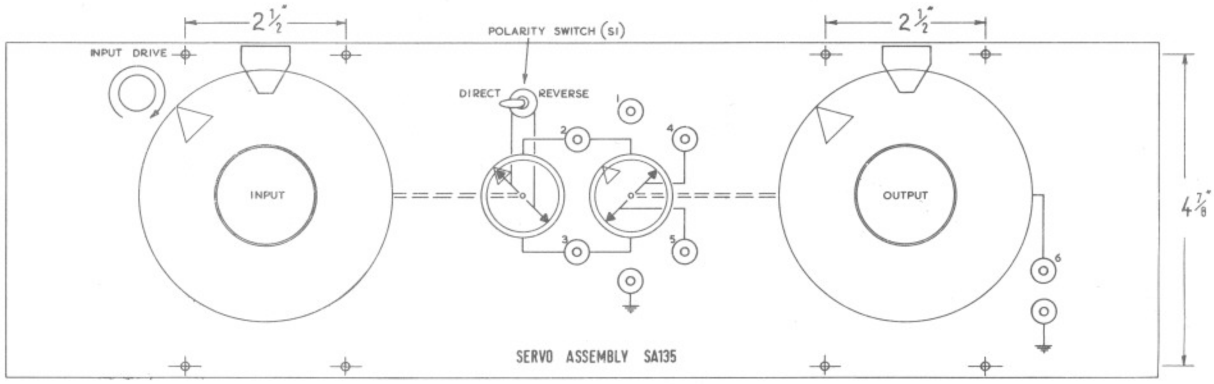
The slider on a separate 10kΩ section of the output potentiometer is brought out to socket (6). This section is energised with about ±10V d.c. so that the output motion can be examined directly. When the output shaft is at 0°, the display slider is nominally at the centre of its track.

Mechanical Details.

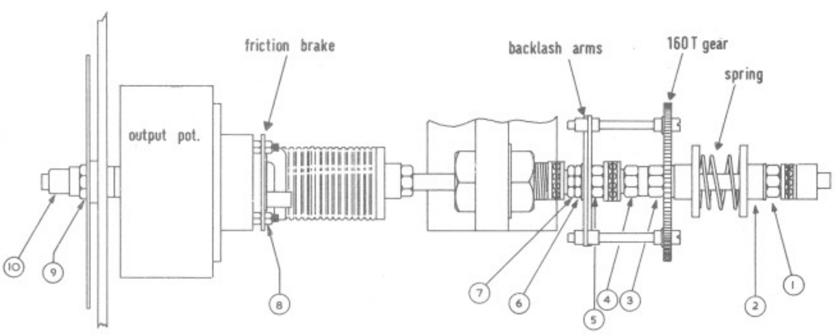
The output system, mounted in the right hand side of the tray, consists of a combined d.c. servo motor with integral permanent magnet tachogenerator driving the output potentiometer through a 16:1 reduction gear. The output system is assembled from the Feedback range of standard mechanical components comprising mounting brackets, bearing hubs with integral ball bearing shafts which can be clamped into mounting brackets, and split hubs by which gears and other items can be locked onto the shafts. The motor drives through a flexible coupling to the gear train which is completely mounted on a single gear plate, and the output potentiometer is driven through a flexible coupling from the gear train output shaft.

Fig. 1b, shows an outline sketch of the final shaft which provides facility to introduce backlash or mechanical resonance. The 160T gear is mounted on a double ended split/plain hub, and is permanently clamped on the plain end of the hub by the threaded end fixing of the spring. If the hexagon portion of the hub (3) is held and the nut (4) on the split end locked up to (3), the split end of the hub will clamp onto the shaft and provide a direct drive to the output potentiometer. The other end of the spring (2) is supported by a single ended split hub (1), and end (2) can be clamped to the shaft by locking (1) into (2).





[a] Outline Front Panel for ES130



DIRECT DRIVE: Lock nut (4) to (3), friction brake (8) off.

BACKLASH: Unlock nut (4) from (3), unlock (1) from (2), friction brake (8) on, hold (5) and set backlash arms to required angle.

RESONANCE: Unlock nut (4) from (3), lock (1) into (2), friction brake (8) off, hold (5) and set backlash arms parallel and perpendicular to driving pins, lock inertia disc onto (10) holding (9).

ES130 PANEL LAYOUT AND MECHANICAL ADJUSTMENTS

[b] Outline of mechanical output system.

FIG. 1

The 160T gear carries two screws with rubber sleeves on the ends which project between the backlash arms which are carried on a single ended split hub (5). Nut (6) partially compresses a crinkle washer to hold the backlash arms against the hexagon portion of the hub (5), and nut (7) is normally locked firmly against nut (6) to clamp the hub to the shaft. The arrangement enables the backlash arm clamping to be adjusted so that the arms can be set by hand to give the desired backlash angle, but there is adequate friction to prevent relative motion between the arms and the hub under normal conditions. The most convenient way to adjust the arms is to hold (5), and set the arms. There is also a friction brake for the output shaft which is used for backlash conditions. This assembly is mounted immediately behind the output potentiometer and consists of a nylon pad on a spring arm which can be brought to bear on an aluminium disc that is locked to the output shaft. For mechanical resonance an inertia disc (normally stored on the vertical spigot in the front portion of the tray) can be screwed onto (10), the threaded portion of the hub which carries the output dial.

The various conditions for the output system are obtained as below :-

Direct Drive: Lock (4) to (3), this clamps the 160T gear to the shaft.

Remove friction brake, ease (8) away from mounting plate, move arm up to locate stop in upper retaining hole in plate.

Remove inertia disc from (10).

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Backlash: Unlock (4) from (3), also unlock (1) from (2).

The gear and spring should be quite free on the shaft. It should be possible to slide the 160T gear out of mesh by compressing the spring and the output shaft should be free to rotate within the backlash limits. Put the friction brake on by easing (8) away from mounting plate so that stop clears retaining hole then moving arm down and engaging stop in lower retaining hole when nylon pad should bear on periphery of disc forming end of bellows coupling.

Remove the inertia disc from (10).

Resonance: Unlock (4) from (3), and lock (1) into (2).

The drive to the output shaft is now through the spring.

Remove the friction brake by easing (8) away from plate to disengage stop from lower retaining hole then moving arm up and engaging stop with upper retaining hole.

Set the backlash arms parallel, and rotate them to about 90° to the line of the screws. This provides a convenient stop to prevent excessive rotation being established. Hold (9) and screw the inertia disc onto (10).

There are a number of additional points which should be noted :-

The left hand portion of the gear plate is quite free, and an alternative output arrangement could be made in this portion.

There is adequate space at the rear of the output shaft to mount some additional component to be driven from the shaft.

There are 4 mounting holes in the panel adjacent to input and output shafts enabling additional units to be supported from these holes to connect to input or output shafts. The nominal fixing centres are given in Fig. 1a.

If the system is to be used for speed control the pinion on the motor shaft should be moved out of mesh to isolate the output potentiometer to prevent excessive wear.

Control Unit (SC125).

The Control Unit contains a separate control chassis (DC259) which carries the main amplifier to operate the servo motor, the operational amplifier, and a number of power supplies, ±300V regulated, +350 unregulated to the output stage, and a 0.5A supply for the motor armature. Fig. 1a, shows the general arrangement of the front panel. The lower portion carries a graphic layout including additional passive networks, and the upper portion carries % error and tachogenerator controls, general purpose monitor meter, and main rotary supply switch.

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Rotary Supply Switch.

This controls all power circuits for the entire system, the detailed switching sequence being as below :-

1. OFF : all supplies off.
2. MAINS ON : all heaters energised, also d.c. supplies available from control chassis but not switched through to amplifiers, etc., potentiometer supplies in servo assembly energised.
3. HT ON : HT supplies switched to amplifiers and rear sockets.
4. ARM ON : Armature supply switched to motor.

In normal experimental use the switch is operated between 2, 3, 4. If for some reason (say) the system is driven into violent oscillation the switch can be rotated to 3 which removes the armature supply and the system will stop.

Error Signal from Servo Assembly.

The error signal from the Servo Assembly can be linked through to socket (1). Below this socket (3) gives access to the % error control (25kΩ) with slider brought out to (4). The attenuator switch S_1 introduces an attenuation 0.1 between (3) and the % error control if required, but the resistance is maintained at 25kΩ from (3) to earth. The parallel RC network between (2) and (3) provides a phase advance network if the error is connected to (2).

Operational Amplifier.

This is a simple general purpose amplifier with a gain of about 500X, bandwidth about 100 Hz on open loop and maximum output about ±40V, ±2mA. The amplifier input and output are directly available at sockets (9), (13), and with the components available on the panel addition, integration, or various compensating networks can be obtained. The zero control is available on the panel, and when the amplifier is not in use the output should be linked to the input, (9) to (13).

Time Constant.

This additional time constant (τ = 0.02 secs) can be connected in the forward path if required.

Servo Amplifier.

The servo amplifier operates the servomotor, and the control characteristic switch (S_2) enables either armature or field control characteristics to be obtained, i.e. the forms

$$\frac{K_1}{j\omega(1 + j\omega\tau_m)} \quad \text{or} \quad \frac{K_2}{(j\omega)^2\,(1 + j\omega\tau_f)}$$

The motor is always field controlled by a push pull output stage, but an internal feedback path is introduced in the 'armature condition which gives substantially a single time constant of τ = 0.16 secs (i.e. frequency break for speed at 1 Hz)

There are two inputs with nominal relative sensitivities of 1.0 (18) and 0.1 (17). The sensitivity from socket (18) is about 11 rads/sec/volt to the output shaft for armature control, or about 330 mA effective in the field/volt for field control. The input impedance is about 2MΩ for either input. When the meter switch (S_4) is set to "servo amplifier" the unbalance across the motor fields is indicated and zero can be set by the zero control. The linear output range is about ±100V on the meter.

The overload monitor point (19) is connected directly to the output stage common cathode resistance and normally stands at about +95V. An oscilloscope connected to this point gives a very sensitive indication of the commencement and extent of amplifier overload.

Motor Tachogenerator.

The motor operates with constant armature current, the fields being differentially energised by the servo amplifier. The tacho generator output is effectively centre tapped to earth across the % tacho feedback potentiometer and R8, sockets (20), (21). The switch (S_3) reverses the connections of (20), (21) to the generator so that adjustable negative feed-back can be obtained from socket (5) either for direct connection to the servo amplifier or to the operational amplifier.

The generator output is 21V/1000 r.p.m., and allowing for the centre tapping and the 16:1 gear ratio, the voltage from (20), (21) to earth is nominally 1.6 volts/rad/sec at the output shaft.

Meter.

The meter is a centre zero voltmeter, 20kΩ/volt, and can be switched by (S_4) to indicate servo amplifier balance or to external sockets with ranges 0/±5/±25/±125 for general purpose monitoring.

Alignment.

If the operational amplifier is introduced in the forward path the resulting 180° phase reversal will cause the closed loop alignment points to change by 180°. The polarity switch in the servo assembly (S_1) reverses the error voltage supply thereby cancelling the 180° introduced by the amplifier. Hence a 0° - 0° alignment can always be obtained.

4. Armature Controlled Motor.

The output element of many electrical control systems is a d.c. shunt motor with the armature supplied by the forward path and the field separately energised. The armature supply might come directly from an electronic amplifier for a small system, or a rotating amplifier (Ward Leonard system or Amplidyne) for a larger system. The general situation is shown in Fig. 5a, where J, F are inertia and viscous friction, and may be analysed as follows. The supply voltage (v_s) is opposed by the back emf and the drop in the armature resistance leading to

$$v_s = i_a R_a + K_b \dot{\theta}_m$$

where $\dot{\theta}_m$ is the motor speed, and K_b is the back emf constant in volts/(radian/second). The torque (T) generated by the motor is used up in accelerating the inertia and overcoming viscous friction giving

$$T = F \dot{\theta}_m + J \frac{d\dot{\theta}_m}{dt}$$

also the torque is proportional to the armature current

$$T = K_t \, i_a$$

and between these three equations the torque can be eliminated to yield

$$v_s = \frac{(FR_a + K_b K_t)}{K_t} \dot{\theta}_m + \frac{JR_a}{K_t} \cdot \frac{d\dot{\theta}_m}{dt}$$

This equation is of the form previously considered for a time constant

$$x(t) = C_1 y(t) + C_2 \frac{dy(t)}{dt}$$

or

$$K_1 x(t) = y(t) + \tau \frac{dy(t)}{dt}$$

so that the motor equation can be written as

$$K_1 v_s = \dot{\theta}_m + \tau_m \frac{d\dot{\theta}_m}{dt}$$

where $$K_1 = \frac{K_t}{FR_a + K_b K_t} = K_s \text{ ; and } \tau_m = \frac{JR_a}{FR_a + K_b K_t}$$

Thus the relation between applied voltage v_s and motor speed $\dot{\theta}_m$ has all the general characteristics of a single time constant system illustrated in Fig. 4, the actual time constant for the motor being a combination of mechanical and electrical parameters. The factor K_s is the 'speed constant' in radians/second/volt d.c.

This result means that if a low frequency a.c. voltage (say a few cycles per second) is applied to the motor the peak speed will lag behind the peak of the applied voltage, and in particular for the frequency

$$\omega = 1/\tau_m = \frac{FR_a + K_b K_t}{JR_a}$$

there will be a lag of 45°, and the maximum speed will be $1/\sqrt{2}$ of the value that would be obtained for a d.c. voltage equal to the peak value of the a.c., see Fig. 5c. Also if a step d.c. voltage (V_s) is applied the speed would run up to a value $K_s V_s$, (d). Using the time constant properties shown in Fig. 4d, it is possible to estimate a motor time constant by its 'run-up' slope.

The above analysis has established a time constant relation between applied voltage and speed ($\dot{\theta}_m$), but for control system analysis a relation between applied voltage and total shaft angle turned through (θ_m) is required. The shaft angle is given by the time integral of velocity

$$\theta_m = \int \dot{\theta}_m dt$$

and this means that from the general equation for a time constant

$$K_1 x(t) = y(t) + \tau_m \frac{dy(t)}{dt}$$

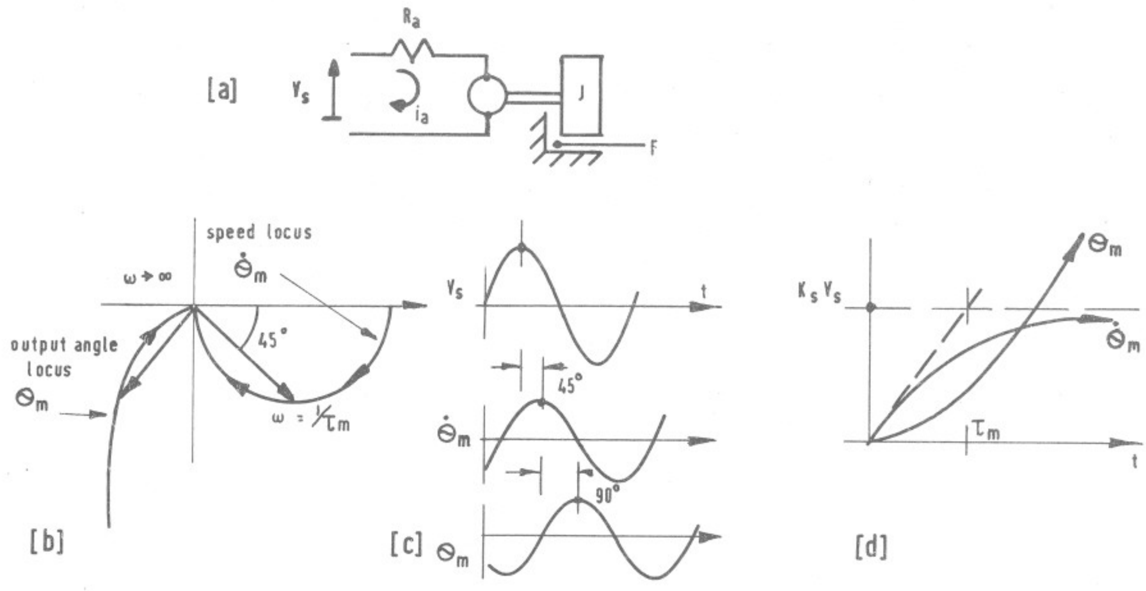

Fig. 5 Armature controlled motor characteristics.

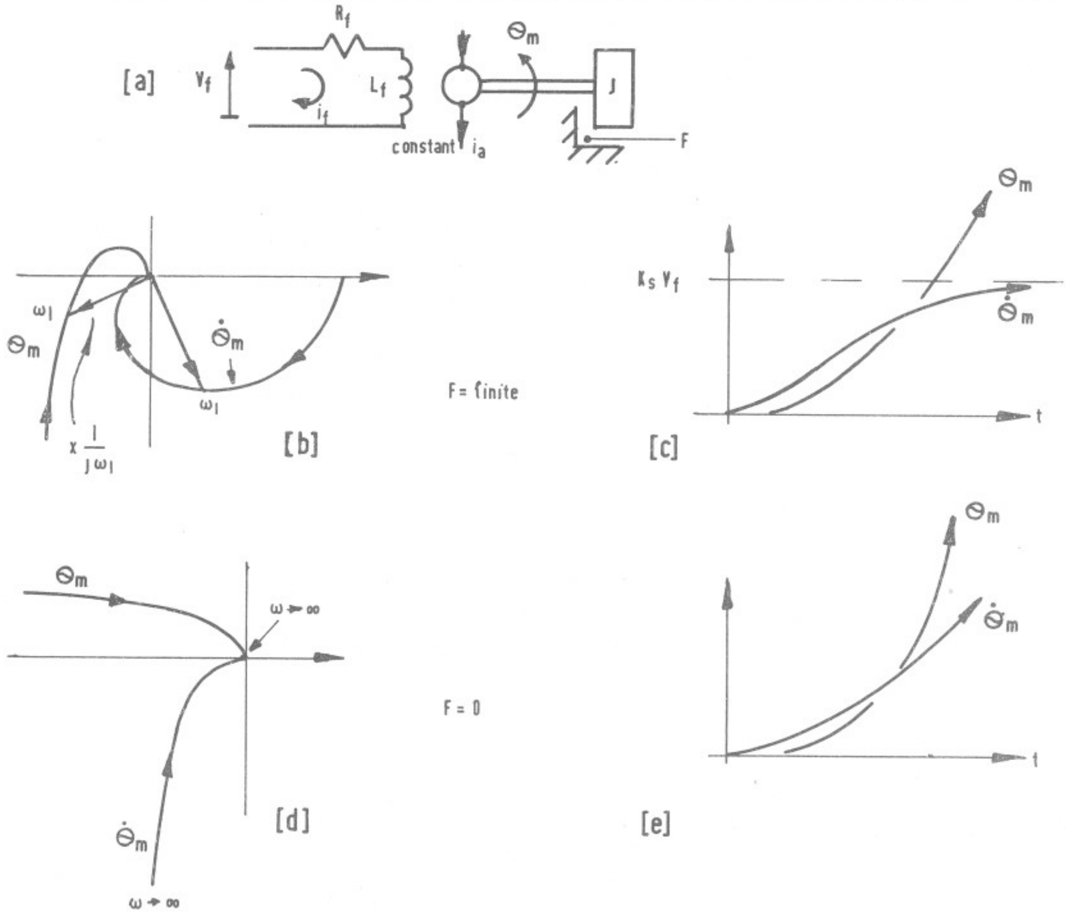

Fig. 6 Field controlled motor characteristics.

an expression must be derived for

$$\int y(t)\, dt$$

both in frequency and transient response terms.

The transfer function

$$\frac{Y}{X}(j\omega) = \frac{K_1}{(1 + j\omega\tau_m)}$$

gives for sinusoidal type signals

$$Ye^{j\omega t} = \frac{K_1 X e^{j\omega t}}{(1 + j\omega\tau_m)}$$

and integrating yields

$$\int Ye^{j\omega t} dt = \frac{K_1 X e^{j\omega t}}{j\omega(1 + j\omega\tau_m)}$$

hence the input voltage : output angle transfer for the motor is

$$\frac{\theta_m}{V_s}(j\omega) = \frac{K_s}{j\omega(1 + j\omega\tau_m)}$$

The result could also be obtained by substituting the fact that

$$\dot{\theta}_m = \frac{d\theta_m}{dt} \; ; \; \frac{d\dot{\theta}_m}{dt} = \frac{d^2\theta_m}{dt}$$

into the motor equation to yield

$$K_s V_s = \frac{d\theta_m}{dt} + \tau \frac{d^2\theta_m}{dt}$$

If then sinusoidal type input and output signals are assumed

$$V_s e^{j\omega t} \quad ; \quad \theta_m e^{j\omega t}$$

and substituted in the equation to give

$$K_s V_s e^{j\omega t} = j\omega\theta_m{}^{j\omega t} + (j\omega)^2 \tau\theta_m e^{j\omega t}$$

$e^{j\omega t}$ may be cancelled to obtain finally

$$\frac{\theta_m}{V_s} = \frac{K_s}{j\omega(1+j\omega\tau_m)}$$

as before.

The transf er developed above, which is very important in control system analysis, implies that the maximum motor output angle always lags 90° on the maximum speed and also the output angle tends to infinity as $\omega \rightarrow o$, which is correct since the motor shaft would rotate continuously in one direction with d.c. applied. For increasing frequency the output angle decreases rapidly. The transfer function locus for output angle may be plotted by multiplying points on the speed locus by $1/j\omega$ to give a locus of the general form shown in Fig. 5b, which gives a lag of 90° as $\omega \rightarrow o$, and approaches 180° as $\omega \rightarrow \infty$ The time relation for supply voltage, speed, and output angle are shown at (c). The speed to output angle relation represents an 'integration', and the transfer function for an armature controlled motor is described as containing 'a time constant and an integration'. It is also important to appreciate that the peak value of the output angle (θ_o) turned through during one cycle of the applied voltage may be several complete revolutions.

To obtain the position response to an input step, the speed step response must be integrated

$$\theta_m(t) = \int_o^t \dot{\theta}_m(t)dt = \int_o^t K_s V_s(1-e^{-t/\tau_m})dt = K_s V_s(t - \tau_m(1-e^{-t/\tau_m}))$$

which is also shown in (d).

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5. Field Controlled Motor.

An alternative method to control a motor is to provide a constant armature current and to control the field energisation as the input signal. This situation is represented in Fig. 6, and may be analysed as below.

For the field circuit

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

the torque generated is

$$T = K_t \, i_f$$

also

$$T = F\dot{\theta}_m + J \frac{d\dot{\theta}_m}{dt}$$

If sinusoidal type input and outputs are assumed as before, then the speed transfer may be obtained as

$$\frac{\dot{\theta}_m}{V_f}(j\omega) = \frac{K_s}{(1+j\omega\tau_f)(1+j\omega\tau_m)}$$

$$K_s = K_t/FR_f$$

$$\tau_f = L_f/R_f$$

$$\tau_m = J/F$$

in which there are two independent time constants, one electrical (τ_f) due to the field, and one (τ_m) due to the purely mechanical parameters of the system. The transfer locus (which is obtained by multiplication of the individual loci for the two time constants), has a limiting angle of 180° as shown in Fig. 6a, and the exact form depends on the ratio between the time constants. Also shown in (b) is the position response locus.

$$\frac{\theta_m}{V_f}(j\omega) = \frac{K_s}{j\omega(1+j\omega\tau_f)(1+j\omega\tau_m)}$$

which is obtained by multiplying the speed locus by $1/\omega$. It should be noted that at a frequency ω_1 it is possible to obtain a finite speed response which lags at 90°, and hence a position response which lags by 180°. For an applied d.c. voltage the final speed is given by

$$\dot{\theta}_m = K_s V_f = \frac{V_f K_t}{F R_f}$$

being inversely proportional to F, so that small viscous loading allows a high final speed.

The speed and position step response have the form shown at (c), and due to the additional time constant the speed response does not have an immediate initial slope and the general expression is not as simple as for the single time constant system.

If viscous friction is absent, i.e. F = O, similar analysis can be carried out to yield

$$\frac{\dot{\theta}_m}{V_f}(j\omega) = \frac{K_g}{j\omega(1+j\omega\tau_f)} \quad ; \quad \frac{\theta_m}{V_f}(j\omega) = \frac{K_g}{(j\omega)^2(1+j\omega\tau_f)} \qquad K_g = \frac{K_t}{JR_f}$$

giving frequency response loci and step response as in (d),(e). The position frequency response always gives an angle greater than 180°, and for the step response there is (theoretically) no limit to the speed since the torque is not opposed by viscous friction, which gives a speed limitation as just mentioned, but is continuously available to accelerate the inertia of the motor and load. Thus the speed locus in (d) approaches infinity for $\omega \rightarrow 0$. In practice the back emf generated across the armature ultimately reduces the constant current for any practical nominal constant current source, and the speed would reach a limiting though very high value. The factor in the transfer function K_g is an acceleration constant; radians/sec^2/volt.

The general characteristics for F = O are applicable to any situation in which a torque is used to position a pure inertia.

Comparison of armature and field control.

Armature control has the disadvantage that the full output power (and some losses) must be supplied from a controlled source to the armature. There are two advantages, first the maximum phase angle only reaches 180° as $\omega \rightarrow \infty$, and second that if F = O (or at least is very small) the system is still first order having a time constant ($\tau = JR_a/K_bK_t$), and the general form of the characteristics is not altered.

Field control has the advantage that the field power required (which must be controlled) is much less than the output power, though a (nominally) constant current

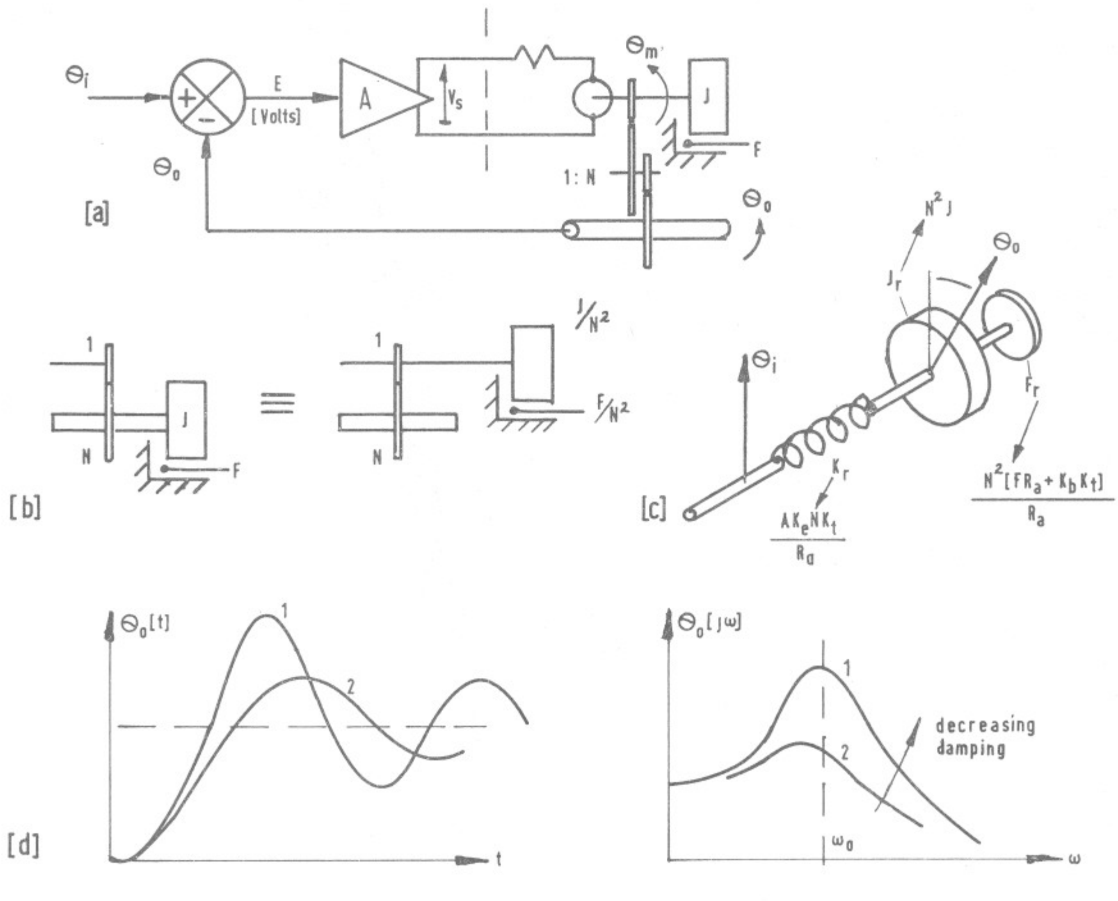

Fig.7 Closed loop system characteristics.

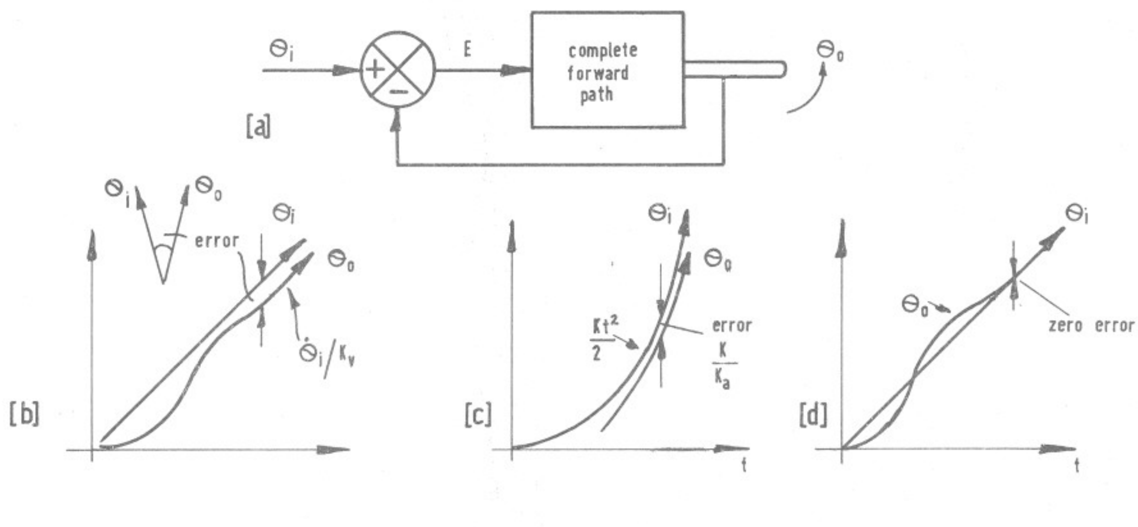

Fig. 8 Error characteristics.

armature supply is required which is an additional complication. The disadvantage is that for F = O (or very small) the characteristics change in a manner which considerably complicates the design problem for a closed-loop system.

OPERATING INSTRUCTIONS AND MEASUREMENT TECHNIQUES.

The actual interconnections and operating conditions required for the system depend upon the experiment in progress, and these are given in detail in the instructions for particular experiments. However, the following general notes may be of assistance :-

Start up procedure, (see Fig. 1a, for panel layout).

1. Set the rotary supply switch to MAINS ON.

   Set the control characteristic switch to ARMATURE.

   Set the meter switch to SERVO AMPLIFIER

   Link sockets (9) and (13) on the operational amplifier.

2. After about 30 seconds rotate the supply switch to HT ON.

   Adjust the servo amplifier zero as indicated by the meter.

   Switch the meter to EXT SOCKETS and check the operational amplifier zero by connecting the meter on ±5 volt range between (13) and (E).

3. Rotate the supply switch to ARM ON.

   It should be possible to control the output shaft rotation by the servo amplifier zero.

The system is now ready for any experimental work. The following is a quick check for closed loop operation :-

Closed loop check.

1. Set the rotary supply switch to MAINS ON.

   On servo assembly, link socket (4) to (1), also (5) to (E), or a low impedance test signal source can be introduced in this link.

   Set polarity switch to DIRECT.

   On control unit, link (1) to (3), set attenuator switch to 0.1, and % error to zero.

   Link (4) to (18) and set the control characteristic switch to ARMATURE.

2. Set supply switch to HT ON, and check servo amplifier zero.

3. Set supply switch to ARM ON, and turn up % error to maximum.

   The system should align and follow rotation of the input shaft.