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DIRECT ACTING ELECTRICAL RECORDING INSTRUMENTS

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I. INTRODUCTION

Direct acting electrical recording instruments are widely used for studies and experiments, as well as for recording of various voltage, current, and power measurements in work areas and plants dealing with electrical power. Their popularity stems from simple construction and ease of operation as well as low cost, which is far below the cost of self-balancing recorders.

Fuji Electric Co., Ltd., for some time has been producing direct acting recording instruments under the name of Ink Recorder S–12K, and has recently developed the new R–12 direct acting recorder which meets the growing demand for a compact recording instrument with superior performance characteristics. Incorporating the best features of former direct acting recorders, this new compact recorder also features a newly adopted recording mechanism (employing an ink sack) and a folding recording chart.

The following is a brief description of the salient features, applications, performance characteristics, and construction of the R–12.

II. FEATURES

1) Rectangular coordinate recording system

An elliptical linkage is employed to provide precise, straight linear movement of the pen, giving accurate, straight time lines, greatly facilitating reading and comparison of recorded data.

2) Two element recorder

In addition to the conventional single element recorder, a two-element recorder can also be provided. This two element recorder has two independent, built-in measuring elements and is advantageous for comparison of recorded values and for recording of data to be preserved for future reference.

3) Recording mechanism featuring the use of an ink sack

An ink sack is employed in the recording mechanism. Since the ink is contained in a plastic sack it will not spill or evaporate. This greatly facilitates maintenance and operation of the recorder.

4) Folding chart

Since a folding chart is used, the amount of recording paper consumed (recorded) can be readily determined at a glance and the recorded data can also be inspected very easily. This folding chart is easy to file and is very handy for recording of data to be preserved for future reference.

5) Built-in accessory box

A built-in accessory box is provided on the R–12 recorder for containing accessories, which otherwise might be easily lost or misplaced. This box provides a convenient storage space for all accessories, except chart paper, greatly facilitating maintenance and operation.

6) Compactness

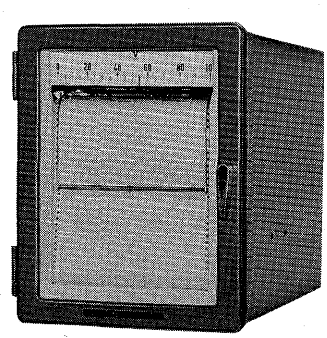
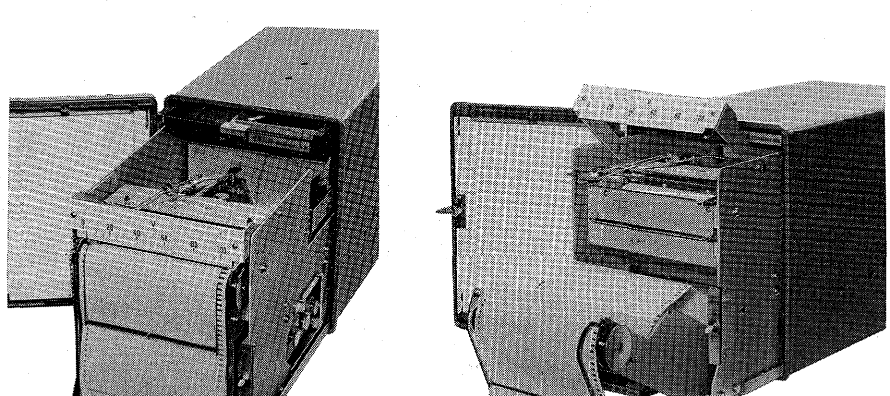


Fig. 1 External view of model R-12



(a) (b)

Fig. 2 Interior mechanism

While the 120 mm recording width is the same as that found in larger conventional S–12K recorders, the space occupied on the panel has been reduced approximately 30%.

7) Fixed pens can be installed

Marking lines such as prescribed or standard values etc., inscribed on the recording paper are convenient when checking the data. Model R–12 recorder can be equipped with fixed pens for recording prescribed or standard reference values at any position within the measurement range.

III. TYPES AND SPECIFICATIONS OF DIREC TACTING RECORDERS

Panel installed (flush mounted) and portable, single or two element recorders are provided.

The recording width for the single element recorder is 120 mm, and for the two element recorder 53 mm+53 mm. The measuring elements of the two element recorder can be optionally combined. However, a two element wattmeter (three phase wattmeter and reactive power meter) cannot be used in the two element recorder.

Types and ratings of the measuring elements are shown in *Table 1*. A moving coil type measuring element is used for dc measurements and an electrodynamometer or rectifier type element used for ac. An iron core electrodynamometer is used exclusively for commercial frequency ac.

Synchronous and pulse motor systems are employed in the recording paper feed mechanism. The former is used for low speeds (10, 20, 30, 60, 120 and 300 mm per hour), high speeds (10, 20, 30, 60, 120, 300 mm per minute) and high-low switching. The pulse motor system is used exclusively for low speeds of 10 to 120 mm per hour with standard pulses of one per second having a 24 v magnitude. (Polarity inversion two wire system.)

Performance fully satisfies accuracy (2.5%) specified for direct-acting recorders as set forth in Japanese Industrial Standard (JIS–C–1203). Withstand voltage is 2000 v ac.

IV. CONSTRUCTION

The R–12 recorder consists of a measuring element, measuring circuit, recording mechanism, recording paper feed mechanism, and case.

1. Measuring Element

A moving coil measuring element is used for dc voltage and current. It features both an external horse shoe magnet and a core magnet to provide adequate torque.

Core type electrodynamometer measuring elements are used for measuring ac voltage, current, power, and reactive power. The electrodynamometer and moving coil element are basically the same in principle and are of identical construction except that the former employs measurement input and the latter a permanent magnet for production of the field in the gaps. Eddy current damping is employed using a damping vane and permanent magnet. Moreover,

Table 1 **Measuring Elements and Ratings**

Measurement Items	Operating Principle (Symbol)	Ratings	Driving Torque	Remarks
Dc Current	Moving coil (M)	2 ma∼30 amp by direct connection 50 amp or greater with external shunt (150 mv)	24 g·cm/Full scale	Uniform scale Center zero scale can also be provided.
Dc Voltage	Moving coil (M)	5 v∼500 v by direct connection 600 v∼2000 v by external voltage divider	24 g·cm/Full scale	Uniform scale Center zero scale can also be provided.
Ac Current	Electrodynamometer (DA)	1 amp∼10 amp by dirrect connection. Greater than 15 amp using a current transformer.	10 g·cm/Full scale	Uniform scale above 20% of scale
Ac Current	Rectifier (R)	5 ma∼10 amp by direct connection	22 g·cm/Full scale	Uniform scale
Ac Voltage	Electrodynamometer (D)	150 v & 300 v by direct connection Greater than 300 v using a current transformer	15 g·cm/Full scale	Square scale
Ac Voltage	Rectifier (R)	10 v∼500 v by direct connection	22 g·cm/Full scale	Uniform scale
Single-Phase Power Three-Phase Power Three-Phase Reactive Power for Balance Circuit	Electrodynamometer (D) (Single element)	Rated current 5, 1, 10 amp Greater than 15 amp using a current transformer. Rated voltage 110 v. 220 v Greater than 220 v using a transformer. Rated power factor (reactive factor) 1 With 110 v, 5 amp 400∼500 w for single-phase 800∼1000 w for three-phase	15 g·cm/Full scale	Uniform scale Zero center scale can be provided
Three-Phase Power Three-Phase Reactive Power (3 or 4-line system)	Electrodynamometer (DII) (Two element)		20 g·cm/Full scale	

Note) All elements of electrodynamometer type use iron cores.

the moving coil elements employ electromagnetic damping using a winding frame. Damping time is 2 or 3 seconds and overshoot is less than 5%. The frequency which the recording pen follows as the measured value changes as a sine wave is approximately 0.1 c/s. Deflection width is less than the actual measurement value when the frequency is higher than that mentioned above.

The rotary motion of the moving coil is converted to linear motion by an elliptic link mechanism, the principle of which is shown in *Fig. 3*. In the figure, the arms ("*a*" and "*b*") are of single unit construction with the recorder pen on one end and a guide pin on the other end. As arm *C* attached to the moving coil rotates, the support point moves in a circular arc and the guide pin simultaneously moves in a straight line along the straight guide slot to give the recording pen an almost perfect straight linear movement. Problems normally encountered in the link mechanism are those related to linearity of the recording, linearity of scale distribution, and recording error due to friction.

1) Recording linearity

To obtain accurate straight movement from rotation motion through the link mechanism, the length of the link arm must be accurately determined. Precise straight linear movement is obtained when $a=b=c$ in *Fig. 3*. However, this condition shows the recording performed on the center axis of the measuring element which is difficult to apply from a construction standpoint.

Thus, conditions more nearly approximate $b^2 \fallingdotseq a \cdot c$ considering overall dimensions so that deviation (D) from the straight line O–Y is zero at both ends of the scale.

These dimensions in the R–12 recorder are: $a=119$, $b=62.5$ and $c=36$, with a deviation (D) of less than 0.2 mm.

2) Linearity of scale distribution and compensation

In *Fig. 3*, deflection width (A) is not proportional to rotational angle α, but to $\sin\alpha$. Therefore, even if the rotational angle α is proportional to input (P), a uniform scale can not be provided due to contraction at both ends of the scale and the deflection width (A) is not proportional to measured input (P). Meters such as the dc meter having uniform scale characteristics are preferably made to have a uniform

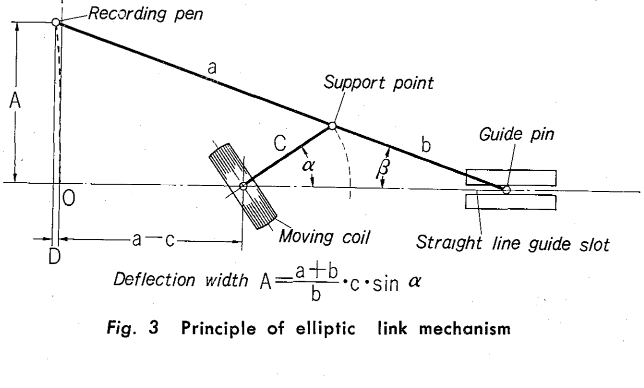


Fig. 3 Principle of elliptic link mechanism

scale through compensation for distortion due to the sine coefficienct. The R–12 recorder compensates for that distortion by the following two methods:

(1) Compensation by controlling torque

Assuming that driving torque M_d is proportional to measured input (P), $M_d=k_1 \cdot P$. The moving portion of the element remains at the position in which both torques (M_c and M_d) are balanced. Since $M_c=-M_d=-k_1 \cdot P$, deflection width (A) is proportional to P. That is, to obtain $A=k_2 \cdot \sin\alpha=k_3 \cdot P$, we must consider that:

$$M_c=-k_1 \frac{k_2}{k_3} \cdot \sin\alpha \fallingdotseq -\frac{k_1 \cdot k_2}{k_3}\left(\alpha-\frac{\alpha^3}{6}\right) \quad (\alpha<1) \ldots\ldots(1)$$

On the other hand, controlling torque (M_c') of the compensating springs composed of a pair of helical springs connected to the arm of the moving coil is:

$$M_c' \fallingdotseq -k_4 \cdot \sin 2\alpha \fallingdotseq -k_4\left(2\alpha-\frac{8\alpha^3}{6}\right) \quad (\alpha<1) \ldots\ldots(2)$$

When a conventional spiral controlling spring is used in conjunction with the aforementioned compensating spring, assuming its torque to be $M_c''=-6k_4 \cdot \alpha$, total controlling torque (M_c) will be as follows:

$$M_c=M_c'+M_c'' \fallingdotseq -8k_4\left(\alpha-\frac{\alpha^3}{6}\right) \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

As a result, equation (3) corresponds to (1) and distortion of the scale due to the sine coefficient is thus compensated.

This method is employed for ac power meters for the R–12 recorder.

(2) Compensation due to the shape of the magnetic pole

If the density of the gap magnetic field is not uniform, which is function $B(\alpha)$ of the rotational angle (α), driving torque (M_d) will be $M_d=k_5 \cdot B(\alpha) \cdot P$.

On the other hand, if controlling torque (M_c) is proportional to α and $M_c=-k_6 \cdot \alpha$, $M_c=-M_d$ at a set position. In the other words, $k_6 \cdot \alpha = k_5 \cdot B(\alpha) \cdot P$. Therefore, the following equation can be employed to make input (P) proportional to deflection width (A).

$$B(\alpha)=\frac{k_6 \cdot \alpha}{k_5 \cdot p} \propto \frac{\alpha}{\sin\alpha}$$

If the density of the magnetic field at the maximum deflection angle (α_m) is represented by B

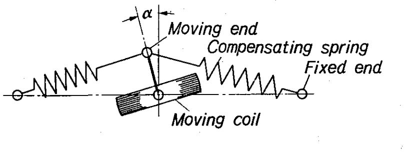


Fig. 4 Compensating spring

(α_m), field distribution can be expressed by the following equation.

$$\frac{B(\alpha)}{B(\alpha_m)}=\frac{\sin \alpha_m}{\sin \alpha}\cdot\frac{\alpha}{\alpha_m}\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

However, rotational angle (α) was considered on the basis of the center of the scale in the previous equation. Thus, field distribution $B(\theta)/B(\theta_m)$ can be expressed as follows when the mechanical zero position is at the end of the scale with the deflection angle from the mechanical zero position represented by θ.

$$\frac{B(\theta)}{B(\theta_m)}=\frac{2\sin\frac{\theta_m}{2}}{\sin\frac{\theta_m}{2}-\sin\left(\frac{\theta_m}{2}-\theta\right)}\cdot\frac{\theta}{\theta_m}\ \cdots\cdots\cdots(5)$$

Therefore, when the size of gap is changed so that field distribution satisfies equations (4) and (5), distortion due to sine coefficient can be compensated and uniform scale can be obtained.

This applies to a dc ammeter and voltmeter for the model R–12 recoder.

(3) Friction error

In a direct acting recorder, friction error is primarily attributed to friction between the recording paper and the pen, with error resulting from the bearings or link mechanism comparatively small (about 20 to 30% of overall friction error). Error due to friction between the recording paper and the pen increases in proportion to the pen pressure. Consequently, it is desirable to have as light a pen pressure as possible within limits of proper recording quality. Effective pen pressure is normally 30 to 50 mg.

The static friction coefficient between the recording paper and the pen varies, depending upon the condition of the pen point and quality of the paper, but is approximately 0.3 to 0.4 based on actual measurement. Static friction force (F) under a 40 mg pen pressure is approximately 14 mg. Thus, friction torque (M_f) is high in proportion to the length of the recording arm.

Considering the fact that the instantaneous movement of the link mechanism shown in *Fig. 3* as driving torque (M_d) overcomes friction torque (M_f), eliminating all other friction attributed to the bearings or link mechanism, "M_f" can be expressed as follows, since $M_d\cdot d\alpha=\mathrm{F}\cdot dA$

$$M_f=-M_d=-F\frac{dA}{d\alpha}=-F\frac{d}{d\alpha}\left(\frac{a+b}{b}\cdot c\cdot\sin\alpha\right)$$

$$=-F\cdot c\cdot\frac{a+b}{b}\cos\alpha\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots(6)$$

$$\therefore\ M_{f\max}=-F\cdot c\cdot\frac{a+b}{b}$$

This friction torque is equivalent to that of a conventional recorder having an arm length of $(a+b)\cdot c/b$. Since $(a+b)\,c/b$ in the R–12 recorder is approximately 105 mm, half of the driving torque is sufficient, allowing for identical friction error found in a conventional recorder having an arm length of 210 mm provided to minimize distortion.

Assuming that pen pressure is 40 mg, and static friction coefficient is 0.35 for the R–12 recorder, the driving torque required to reduce maximum friction error below 1% of scale width is approximately 15 g·cm, since friction torque (M_f) is 0.15 g·cm. However, friction error for ac meters is greatly reduced in the neighborhood of rated input, since driving torque fluctuates. Friction error in square characteristics meters such as in ac ammeters or voltmeters is further reduced, since differential torque (deviation factor of driving torque) changes considerably and friction error becomes much smaller than in meters having uniform scales.

(4) Ac Ammeter Scale Distribution

Essentially, electrodynamometer type ammeters are of square scale characteristics and effective value indication. R–12 recorders are designed with non-uniform core gap dimensions so that uniform scale is provided at above 20% of the end scale.

Assuming that the applicable measuring range is from 20 to 100%, and that the deflection angle at 20% is approximately 11% of the maximum deflection angle (θ_m), the relationship between rotation angle (θ) and measured current (I) for obtaining uniform scale at above 20% can be expressed as follows:

$$\frac{I_m}{I}=\frac{10\,\theta_m}{9\theta+\theta_m}=\frac{10}{9\frac{\theta}{\theta_m}+1}=\frac{10}{9n+1}$$

$$(I\leqq 0.2I_m)\ \cdots\cdots\cdots\cdots(7)$$

Where, I_m is rated current, $n=\theta/\theta_m$

Here, the density of the magnetic field in the gap is proportionate to the coefficient of gap dimension, $B(\theta)$, and measured current I. When the density is represented as $B(\theta)\cdot I$, driving torque (M_d) is proportional to $B(\theta)\cdot I^2$. $B(\theta)$ is proportional to θ/I^2 since the controlling torque (M_c) is proportional to θ and the moving portion is located at the position at which M_d and M_c are balanced. As a result, the magnetic field distribution coefficient on the portion of the uniform scale can be represented by the following equation:

$$\frac{B(\theta)}{B(\theta_m)}=\left(\frac{I_m}{I}\right)^2\cdot\frac{\theta}{\theta_m}=\left(\frac{10}{9n+1}\right)^2 n=\frac{100\,n}{(9n+1)^2}$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(8)$$

On the other hand, the magnetic field coefficient in the gap of the constant radius from the center for the shape of magnetic pole shown in *Fig. 5* can be expressed by the following equation:

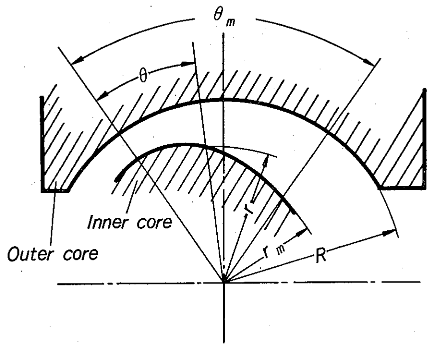


Fig. 5 Ac current recorder cores (Ac ammeter)

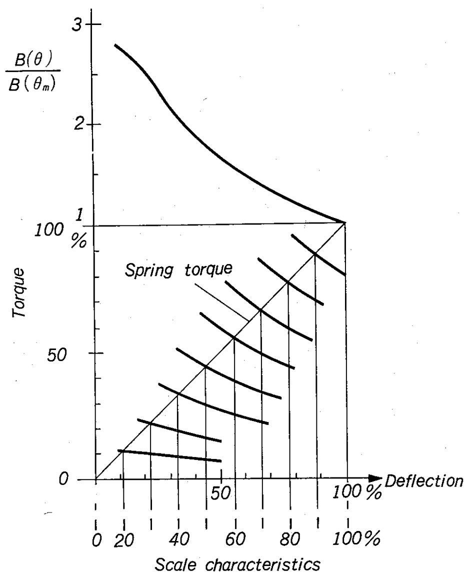


Fig. 6 Ac current recorder scale characteristics

$$\frac{B(\theta)}{B(\theta_m)} = \frac{\log R - \log r_m}{\log R - \log r} = \frac{\log R/r_m}{\log R/r} = \log_{R/r}\frac{R}{r_m} \quad \text{.................}(9)$$

From equations (8) and (9), the relationship between the radius of the inner core and angle for obtaining a uniform scale can be expressed by the following equation:

$$r = R\left(\frac{r_m}{R}\right)^{(0.9n+0.1)^2/n} \quad \text{where a} \quad n = \frac{\theta}{\theta_m} \quad \text{.........}(10)$$

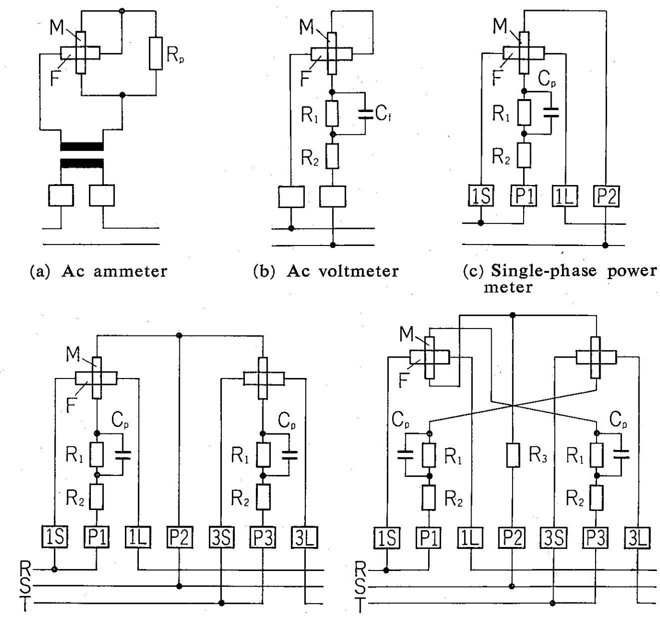
Fig. 6 shows the results of equation (8) and scale characteristics.

2. Measuring Circuit

The R–12 recorder measuring circuit is nearly the same as that for indicating instruments. The circuit for the ac meters is shown *Fig.* 7 for reference.

Since current flows through the moving coil in the ammeter, the secondary current of the auxiliary current transformer is maintained at approximately 1 amp The auxiliary current transformer becomes saturated when excessive current flows; therefore, the current flowing through the moving coil is limited to under 3 amp. Thus, the moving coil which has a comparatively low excessive current strength is protected.

Errors occur in the ac wattmeter due to changes in the power factor when the phase lag of the gap field to the circuit current and that of the moving coil current to the voltage do not match. In the indicating meters the former usually has a greater phase lag than the latter. However, the recorder has a greater phase lag in coil current due to high inductance of the moving coil, which is compensated by a capacitor, as shown in the figure. In the ac measuring circuit, there is a three-phase power meter for the balancing circuit, reactive power meter (single-element), and rectifier ammeter and voltmeter in addition to the meters shown in the figure.



(d) Three-phase power meter (e) Three-phase reactive power meter

Fig. 7 Ac recorder connection diagram

M: Moving coil
F: Field coil
Rp R1-3: Resistors
Cf: Frequency compensating capacitor
Cp: Power factor compensating capacitor

3. Recording Mechanism

The R–12 recording mechanism consists of an ink sack, junction pipe, soft tube, recording pen, and recording arm as shown in *Fig. 8*. They can be readily removed as shown, in the figure. The ink sack is employed in nearly every recorder manufactured by Fuji Electric. It is perfectly shielded except at the very end of the pen tip. This ink sack recording mechanism has the following advantageous features:

(1) No syringe or the like is required to feed the ink to the top of the pen at the beginning of writing. Ink is easily fed by pressing the ink sack with the fingers.
(2) If the pen tip becomes choked it can be freed by forcing ink out of the sack.
(3) Since evaporation of the ink is prevented, ink consistency is maintained at a constant value.

Therefore, the pen seldom becomes choked.

(4) There is no danger of spilling the ink when the recorder is lifted or carried while recording.

(5) Immediate recording can be made after the recorder has been out of service for an extended time and the recorder can be readily transported by merely covering the top of the pen. (As it is, R–12 recorders are designed for inserting the pen into a rubber holder near the recording arm after the recorder pen is removed from the recording arm.)

Saran sheet is used for the ink sack which must be strong as well as soft and pliable.

Recording is performed by capillary action; thus, it is not necessary to apply pressure to the sack.

If the ink sack is positioned too high, too much ink will be fed to the pen. Thus, the height of the sack is regulated according to conditions.

Ink sack capacity is approximately 10 cc although the lower 2 cc in the bottom of the sack is virtually unused at normal ink sack heights. Thus, actual effective capacity is approximately 8 cc. Although the length of the line which can be recorded by a single ink sack varies, depending upon recording conditions, a single ink sack will normally record a straight line approximately 1000 to 5000 m in length. In other words, recording equal to two recording paper lengths, that of single recording paper is 32 m, can be provided at a feed speed of 20 mm per hour, which lasts approximately four months.

In the recording system, ink is applied through tubing. If the tubing is heated, air bubbles may develop in the ink interrupting ink flow. This is carried by the air dissolved in the ink, and released in the form of air bubbles as the ink is heated. These air bubbles increase in size and the ink evaporates into the air bubble. To prevent this from occurring, the air content of the ink is reduced by heat (approximately 60°C) before the ink is applied to the sack.

Although it is convenient for the rated or limiting values to be inscribed on the recording paper when checking data, such values are scarcely provided due to the increased cost involved in printing the recording paper and disadvantages from the standpoint of supplementing the special recording paper. To satisfy this requirement R–12 recorders can be provided with fixed pens at any position within the measurement range.

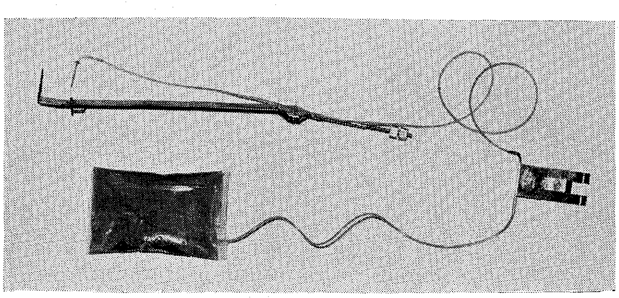


Fig. 8 Pen and ink

4. Recording Paper Feed Mechanism

Synchronous and pulse motor recording paper feed mechanisms are employed. Except for the motors, the mechanisms are of almost identical construction with respect to the replacement gear and the recording paper mechanism. The drive unit for switching speed (per minutes per hour) has two synchronous motors, as shown in *Fig. 9*, coupled to the same axis through a roller clutch mechanism. Recording paper is fed by a single motor to which the input is applied.

The roller clutch outer ring is attached to the axis and a cam is attached to the gear (G_2) as can be seen in the figure, the cam can pivot freely in the direction of the arrow, but will not turn in the opposite direction and be coupled with the clutch outer ring. This clutch is so designed that there is little backlash when engaged from slip rotation.

Recording paper feed speed can be changed in six stages from 10 mm to 300 mm by setting of the replacement gear.

To replace the recording paper, lower the recording paper mechanism forward. Folding chart recording paper is used. When employing folding chart recording paper in a recorder having low driving torque, friction error will be greater at the folded part of the paper. However, this type of folding paper is extremely effective for checking data and for filing data to be retained for future reference.

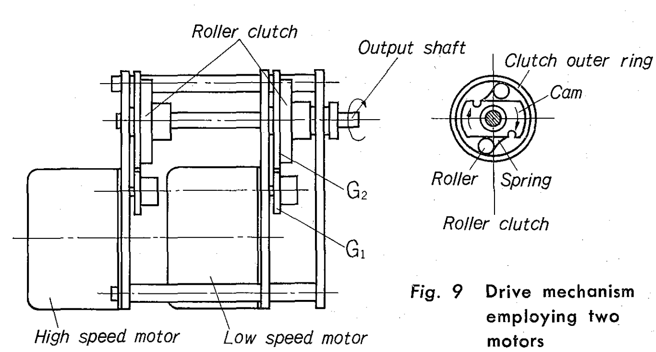


Fig. 9 Drive mechanism employing two motors

5. Construction of Other Components

The interior mechanism of the R–12 type recorder, as seen in *Fig. 2*, is of a drawer construction and can be withdrawn during recording for checking or inspection of the interior mechanism.

An accessory box is provided inside the top of the case. This accessory box is accessible when the interior mechanism is withdrawn. For panel installation 4 mm meter terminal screws are employed with a wide space provided between the terminals for assured secure connections. Insulated terminal nuts are provided on the meter terminals in portable recorders and an inserting plug can be used.

Reference:

1) Dr Louis Merz: ATM J. 271-13 1951.