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A Corrected Speed Tachoscope

By

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SUMMARY

It is often desirable in testing aerodynamic compressors to take all readings at fixed corrected speeds rather than true speeds. This corrected speed is defined as the actual shaft speed divided by the square root of the ratio of the absolute air inlet temperature to the standard temperature (288°K.). With the instrument described, this is possible with high accuracy (error < 0.1 per cent) without further complication than the setting of a dial to the observed air inlet temperature.

The latter operation could be dispensed with and the correction obtained directly from a temperature sensitive device such as a thermistor or a resistance thermometer element.

CONTENTS

ILLUSTRATIONS

1.0 Introduction

When testing turbo-machines, it is sometimes preferable to take readings at definite corrected speeds rather than absolute speeds. Not only does this simplify plotting, comparison of results and obtaining check points but it also avoids difficulties which arise in interpreting results when the inlet temperature fluctuates during a long test.

Few direct reading tachometers can attain an accuracy of ± 0.1 per cent. Even with an accurate instrument of this sort, reference to a chart or table is necessary to determine the required shaft speed at the inlet temperature prevailing before the shaft speed can be set. As, in general, the required absolute shaft speed will be between values marked on the tachometer scale. the process of setting and maintaining this speed will be tedious.

Tachometers which either count the number of revolutions of the shaft (or some multiple of the number of revolutions) in a given time or measure the time for a fixed number of revolutions are capable of attaining an accuracy of better than ±0.1 per cent but because the speed is not indicated continuously, they are more difficult to use for the setting of a fixed speed than direct reading instruments.

The device to be described avoids any disadvantages of the above instruments. The operations necessary are the setting of a dial to the measured air inlet temperature and then the adjustment of the shaft speed to give a stationary pattern on a stroboscopic indicator.

This corrected speed tachoscope was designed specifically for use in testing supersonic and transonic compressors. As the operating conditions of these types of compressor can change rapidly with relative Mach number, it is essential in this case that tests should be at constant corrected speeds (as then the relative Mach number will be independent of inlet temperature variations).

2.0 Method of operation

An accurate frequency is generated which can be compared with the shaft speed by stroboscopic means. If the frequency of this source is dependent on the air inlet temperature such that the corrected frequency (actual frequency x $\sqrt{\frac{288}{T}}$, where T is the absolute inlet temperature) is constant at some convenient value, it follows that the shaft speed will also be corrected whenever a stationary image on the stroboscopic disc is obtained.

A convenient and inherently accurate method of generating this frequency is to add to an accurate, constant frequency source a variable increment which is a function of the inlet temperature. In practice, the maximum value of this increment is a small fraction of the accurate constant frequency ($^1/_{30}$ for a range of -5°C. to $+35^{\circ}$C.) and therefore the permissible error can be quite large (about ±3 per cent) without exceeding ± 0.1 per cent total error. If necessary, the range of the instrument can be extended provided the increment error is reduced or the allowable error can be greater than 0.1 per cent

Frequency generators using a tuning fork or a quartz crystal as the controlling element can attain the desired accuracy (error < ±0.01 per cent). The contact maintained tuning fork is probably the least expensive, simplest and most reliable of the above frequency generators.

The particular instrument to be described uses an Elinvar contact maintained tuning fork and an electronically controlled motor to generate the increment frequency. The accuracy of the first frequency is ±0.01 per cent and of the second < ±1 per cent. By frequently checking the instrument calibration, the last figure can be reduced to about ±0.1 per cent (see Section 5.0). In this particular design where the range is -5°C. to +35°C., the maximum total error (at -5 or +35°C.) will be about 0.04 per cent. This error will of course reduce as the inlet temperature approaches 15°C.

3.0 General description of instrument

The increment frequency is determined by the speed of a shaft driven through the gear box C by the motor A (see Figure 1). The motor speed is governed electrically by the electronic servo-amplifier B. The capacity frequency adder D sums this frequency and the frequency generated by a tuning fork (not shown) and feeds the resultant signal to the trigger circuit E. This circuit generates pulses which trigger the stroboscope tube F. This stroboscope tube illuminates a disc driven at the shaft speed, or a fraction of it, by a synchronous electric coupling. The stroboscopic rings which are printed on this disc (most conveniently by a photographic process) are designed so that one or more of the rings appears stationary at the shaft speeds at which it is desired to take readings.

A standard engine speed indicator is also required to provide an approximate indication of the shaft speed.

Should a fault develop in the correcting circuit, testing can be continued at constant actual speed as provision is made for operating the stroboscope tube directly from the tuning fork contacts.

Provision is also made for the checking of the increment frequency calibration (see also 5.0).

A similar technique to the above can be used if it is more convenient to control the stroboscope tube by the shaft speed and the stroboscopic disc speed by the instrument.

4.0 Details of circuit (see Figure 2)

4.1 Motor and drive

The motor speed is stabilised by a simple electronic servo-amplifier which enables the motor speed to be accurately controlled and causes the speed to be virtually independent of supply voltages and load.

The motor armature is fed from a 24 volt direct current supply through a 24 volt 24 watt bulb. This bulb is to reduce armature current variation with motor load and speed.

The motor field excitation is proportional to the output of the servo-amplifier which, in turn, is proportional to the amplifier input, an applied control voltage minus the generator voltage. This generator is separately excited from a stabilised high tension supply and is directly coupled to the motor. If the motor is lightly loaded and if the amplifier gain is high, it can easily be seen that the rotor speed will increase or decrease until the generator voltage equals the applied control voltage. If this control voltage is obtained as in Figure 2 from a potentiometer, the potentiometer will form an effective linear motor speed control. This control is calibrated directly in degrees centigrade, the air inlet temperature (see Appendix I).

If so desired, this control can be operated remote from the instrument and connected through a length of screened cable. The motor speed can be controlled automatically from the inlet air temperature if the control voltage is derived from a temperature sensitive device. As the control voltage is about -20 to +20 volts, a very sensitive element is necessary.

The impedance of the circuit is however very high and therefore a high impedance element (or several in series) can be used. Suitable elements are the thermistor and the resistance bulb. The first is non-linear and therefore series and shunt resistors in the thermistor circuit are necessary to obtain the desired output/temperature characteristic. Similar but smaller corrections are necessary if a resistance bulb is used. As the accuracy of operation of an automatic correction circuit would be difficult to check, such a circuit has not been incorporated in this particular design.

Because the output of the generator is not pure direct current but contains an appreciable amount of ripple, a simple filter must be incorporated between the generator armature and the amplifier. Otherwise the efficiency of the motor control would be impaired and high alternating voltages would be developed in the motor fields. This filter introduces an additional phase shift in the servo-loop and therefore the system is more liable to hunt. Stability is ensured by attaching a flywheel on the rotor shaft. A reduction in the rate of response caused thereby is unavoidable but is in no way detrimental in this application.

The motor drives the capacity frequency adder through a step down gearbox of ratio 64 : 1 for the 25 c.p.s. unit or 32 : 1 for the 50 c.p.s. unit.

1.2 <u>Capacity frequency adder</u> (see Figure 3)

Here the 50 c.p.s. version is described. The 25 c.p.s. version is similar but uses two moving vanes and three stators.

This device adds two frequencies, one the speed of the rotor and the other a four phase constant frequency electrical signal applied to the stator, the sum appearing as a single phase electrical signal on the rotor.

The stator is split into four quadrants, each of which is fed with an equal voltage fed from a constant frequency source. The phase of the signals on the quadrants advance round the stator in 90° steps. These signals are obtained from the output of the phase splitter; two by attenuating the output 2 : 1 and the others by passing through resistance-capacitance networks (giving 90° phase shift and 2 : 1 signal attenuation). The rotor, which is driven by the motor via a gear box, consists of a single disc rotated about an axis passing midway between the centre and circumference. The clearances between this disc and the stators are about 0.02 in. This device is basically the same as that described in Reference 1.

Because the capacitance between the plates is small and the working frequency low, it is essential that the output of the adder be fed into a high impedance - low capacitance circuit (impedance of the order of 300 MΩ). The capacitance of the adder device could, however, be increased, if necessary, by filling with an insulating fluid such as transformer oil.

A further type of adder using a "Magslip" was tested but it proved to be inferior to the capacity type in this particular application.

4.3 High impedance - low capacitance circuit

This consists of a high μ (amplification factor) valve connected as a cathode follower. To avoid introducing across the input the capacitance of the screened lead between the adder and the cathode follower, an intersheath is used which is fed from the cathode of the valve. Thus the intersheath potential will follow the input voltage in the same phase and therefore this lead will introduce little further capacitance into the circuit.

The attenuation of the signal through the phase changer, adder and input circuit of the prototype was about 5 : 1.

4.4 Electronic trigger circuit

This circuit employs positive feedback to make the effective voltage gain infinite and so it will convert the sinusoidal waveform from the cathode follower into a square wave. This square wave is differentiated by a resistance-capacitance network to give a series of pulses - one positive and one negative per cycle. The characteristics of the stroboscope tube are such that only the negative pulse can cause it to conduct.

4.5 Trigger circuit for the tuning fork contacts

The power supply for this circuit is derived from the stroboscope tube supply via a potential divider and resistance-capacitance circuit. When the tuning fork contacts close, a condenser is rapidly discharged - thereby giving a negative voltage pulse which can trigger the stroboscope tube. Upon opening the tuning fork contacts, the above mentioned condenser will recharge ready for the next cycle.

4.6 Selector switch

This switch selects the source of pulses - either from the electronic trigger or the tuning fork trigger - and feeds them to either the internal calibrating stroboscope or the external tube on the tachoscope. When on the first position, the calibration check position, pulses from the tuning fork trigger operate the internal tube strobing the rotor shaft. On the second position, the normal operating position, pulses from the electronic trigger operate the tachoscope stroboscope tube. On the third position, used if the rest of the apparatus develops a fault, the tuning fork triggers the tachoscope stroboscope tube directly.

4.7 Power units

Two entirely separate power units are incorporated, one supplying the stroboscope tube and the tuning fork trigger and the other the rest of the apparatus. As well as a 230 volt 50 c.p.s. supply, a 24 volt direct current supply is required. This supply is usually derived from a communal power unit and so no separate unit is shown.

5.0 Calibration check

As mentioned previously, provision is made so that the motor shaft can be strobed at the same frequency as that of the tuning fork. This enables an accurate check to be made on the calibration near both ends of the temperature scale (at motor speeds of ±3,000 r.p.m. for a 50 c.p.s. fork).

6.0 Auxiliary equipment

As the apparatus requires a pure sinewave signal input (of about ½ volt r.m.s.), means have to be provided to obtain this from the contact maintained tuning fork. Two methods have been successfully tried, one using an electromagnetic pick-up (from a headphone earpiece) and the other using a two section π filter to remove harmonics from an approximate square wave obtained by interrupting (by means of the tuning fork contacts) a voltage supply from a battery. If the first type were connected to the fork directly, excessive damping would result and the frequency stability would be impaired. To overcome this difficulty, it was fixed to a slave vibrator which was maintained vibrating electromagnetically using the tuning fork contacts (see Figures 4 and 5 and general layout Figure 6).

Many other methods would no doubt be just as satisfactory.

7.0 Conclusions

A device has been described with which a turbo-machine can be set at selected corrected speeds with an error of considerably less than 0.1 per cent in the inlet temperature range -5 to +35°C.

This instrument by no means demonstrates the limit of the technique and larger ranges can be accommodated by suitable design.

This technique by which a calibrated variable frequency is added to an accurate constant frequency may find other applications in other fields.

REFERENCES

No.	Author	Title
1	Terman F. E.	Radio Engineer's Handbook p. 949 8th Edition. McGraw - Hill Book Company Inc. New York and London. 1943.

APPENDIX

Determination of the motor speed - temperature relationship

The corrected speed of a turbo machine is defined as

$$N_{corrected} = \frac{N_{actual}}{\sqrt{\frac{T}{288}}} \quad \text{where T is the absolute inlet temperature}$$

$$\text{Therefore } N_{actual} = N_{corrected}\sqrt{\frac{T}{288}}$$

If the actual speed is set using a stroboscopic indicating means as described in the main text, the frequency relationship is the same as the speed relationship.

$$\text{That is } f_{stroboscope} = f_{tuning\ fork}\sqrt{\frac{T}{288}} = f_{tuning\ fork}\sqrt{1 + \frac{t}{288}}$$

$$\text{where } t = T - 288$$

Expanding by means of the binomial theorem we obtain

$$f_{stroboscope} = f_{tuning\ fork}\left\{1 + \frac{1}{2}\left(\frac{t}{288}\right) - \frac{1}{8}\left(\frac{t}{288}\right)^2 + ---\right\}$$

$$= f_{tuning\ fork} + f_{tuning\ fork}\left\{\frac{1}{2}\left(\frac{t}{288}\right) - \frac{1}{8}\left(\frac{t}{288}\right)^2 + ---\right\}$$

Therefore the increment frequency is

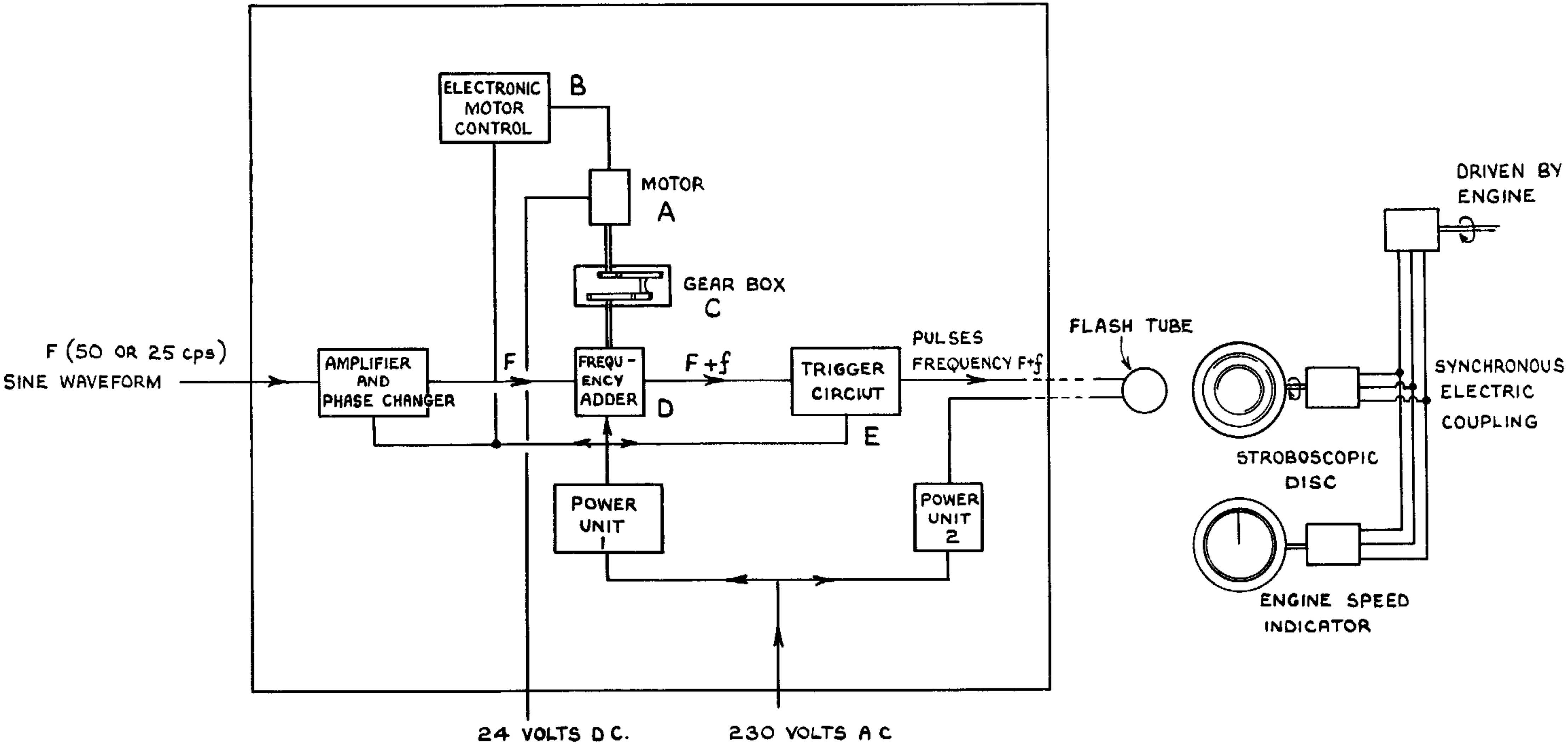
$$= f_{tuning\ fork}\left\{\frac{1}{2}\left(\frac{t}{288}\right) - \frac{1}{8}\left(\frac{t}{288}\right)^2 + ---\right\}$$

$$\text{This must equal } \frac{\text{Motor speed}}{60 \times \text{gear box ratio}}$$

$$\text{or Motor speed} = 60 \times \text{gear box ratio} \times f_{tuning\ fork}\left\{\frac{1}{2}\left(\frac{t}{288}\right) - \frac{1}{8}\left(\frac{t}{288}\right)^2 + ---\right\}$$

Usually, only two terms in this expansion are necessary.

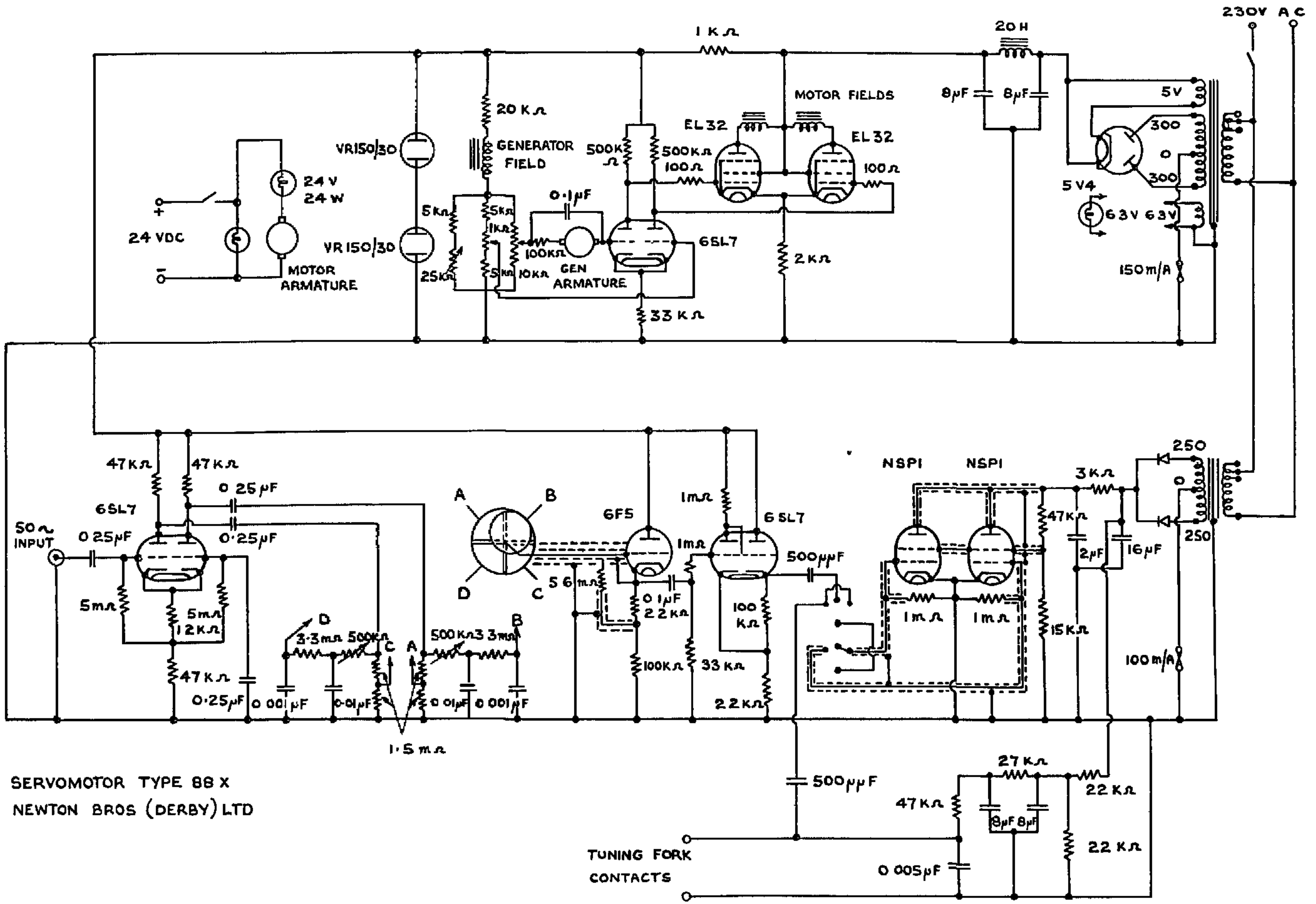
The motor speeds are thus calculated and the dial calibrated with the aid of any suitable tachometer (e.g. a Hasler)



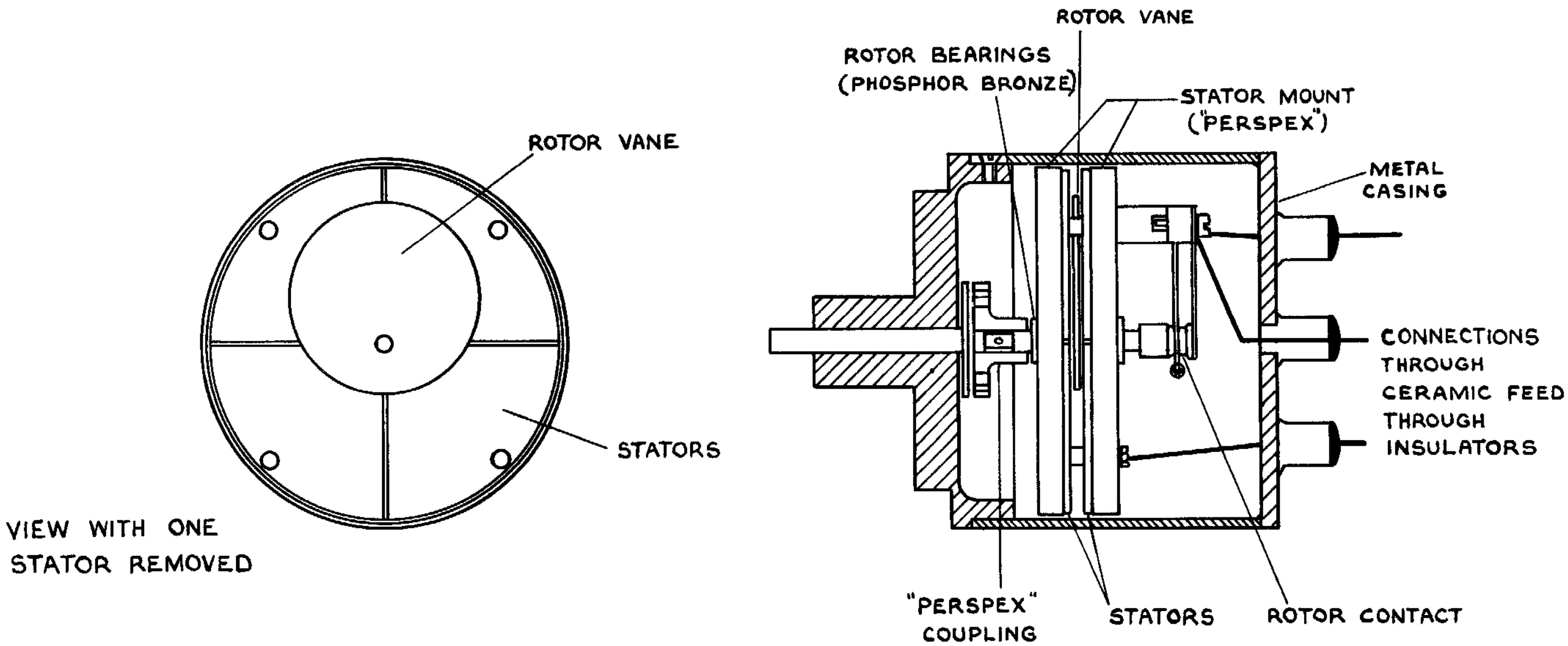
BLOCK DIAGRAM OF CORRECTED SPEED TACHOSCOPE

FIG. 1

FIG. 2



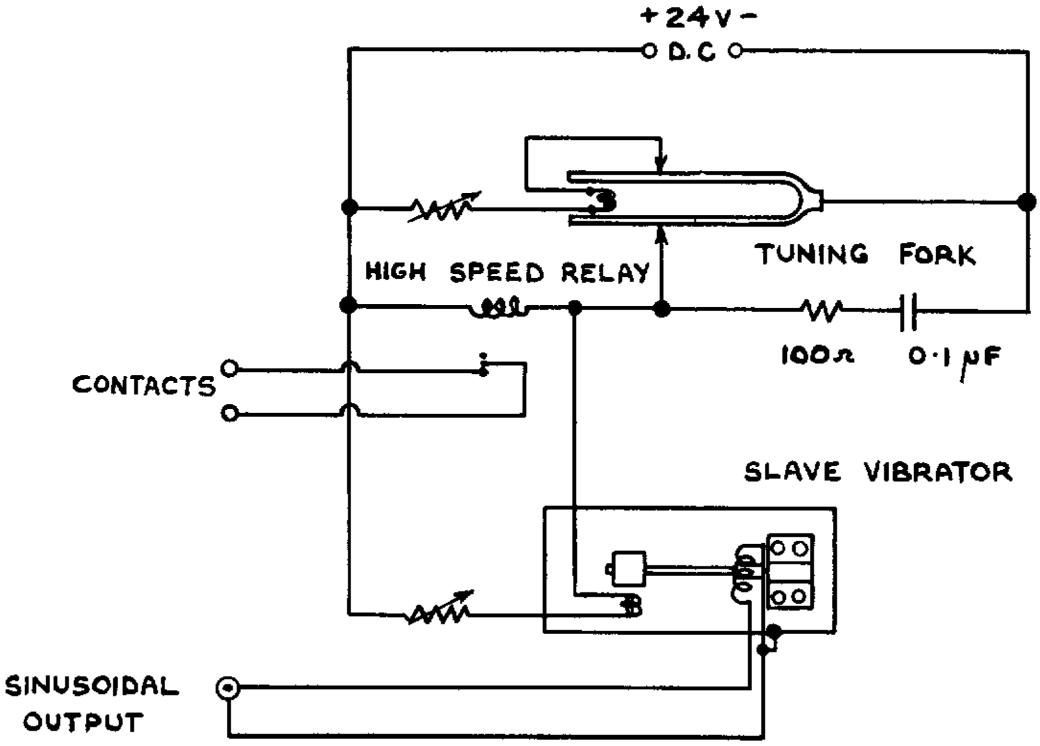
CIRCIUT DIAGRAM OF CORRECTED SPEED TACHOSCOPE



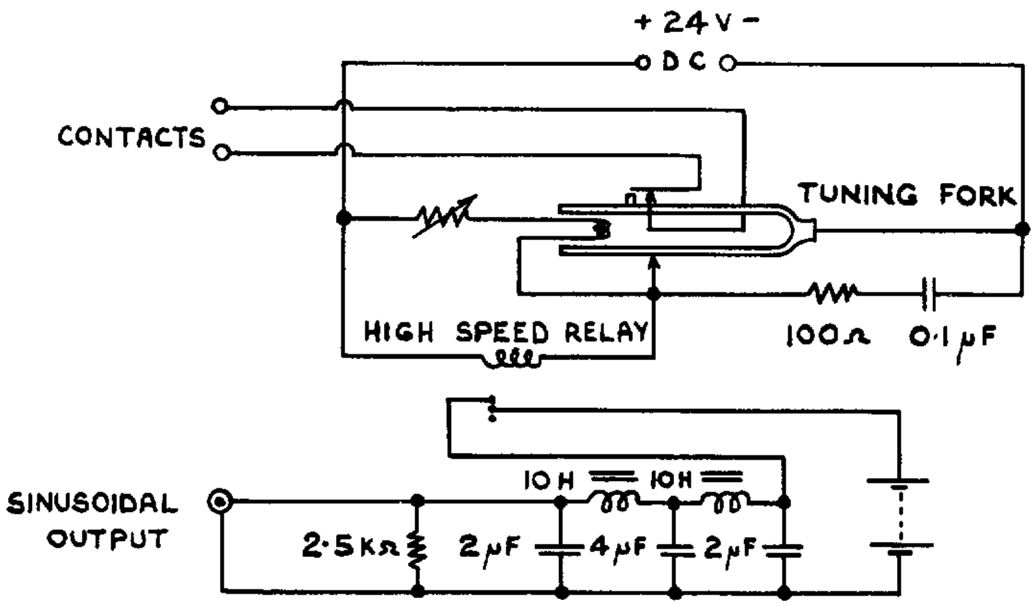
CAPACITY FREQUENCY ADDER

FIG. 3

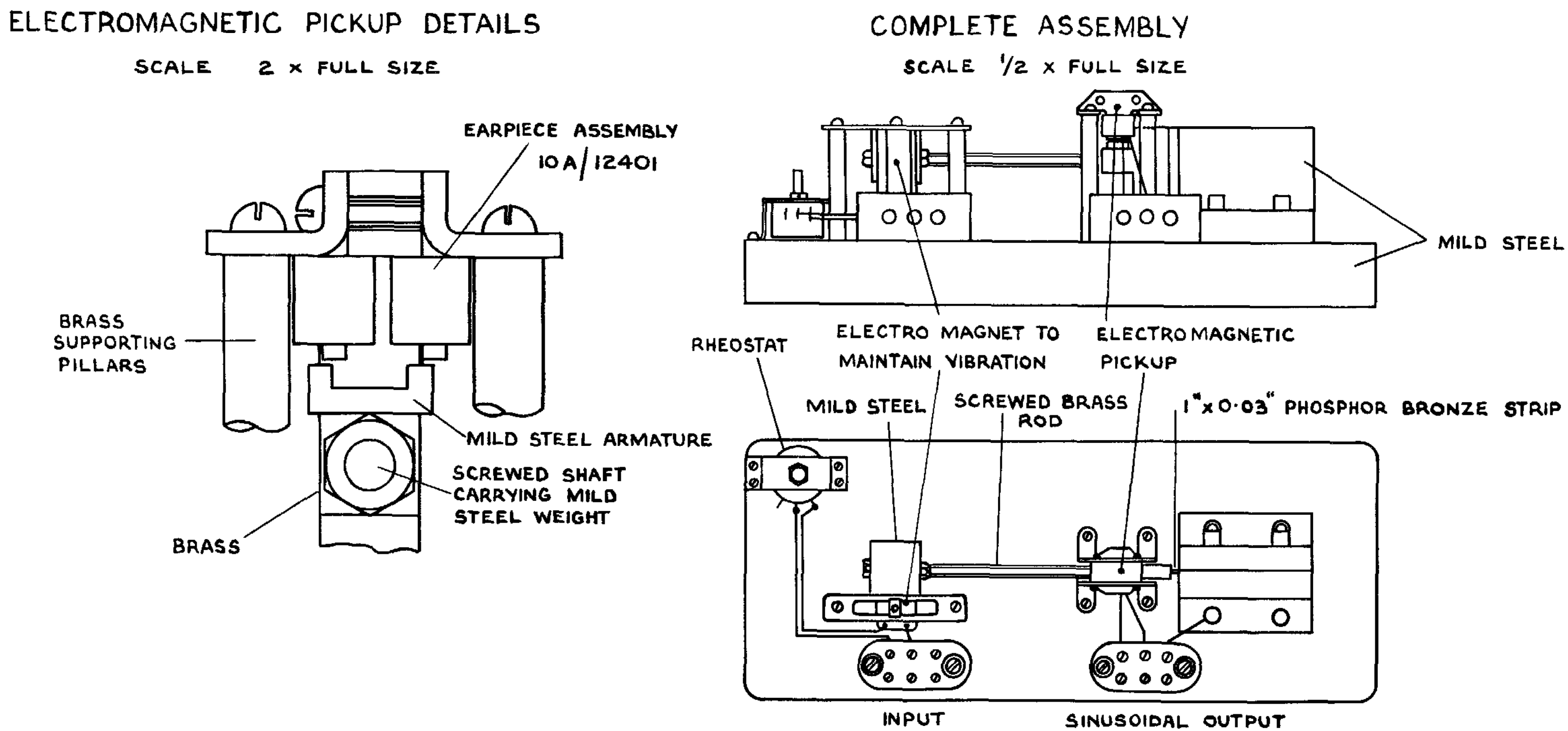
1. USING SLAVE VIBRATOR AND ELECTRO-MAGNETIC PICKUP



2. USING ELECTRICAL FILTER



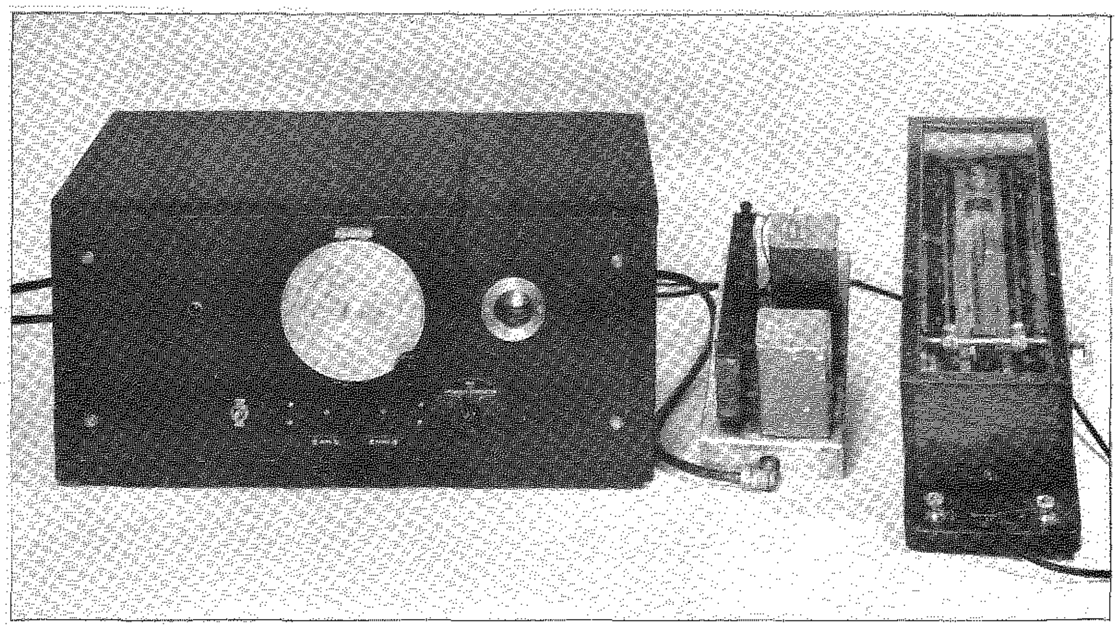
COMPONENT VALUES IN FILTER FOR 50 CPS



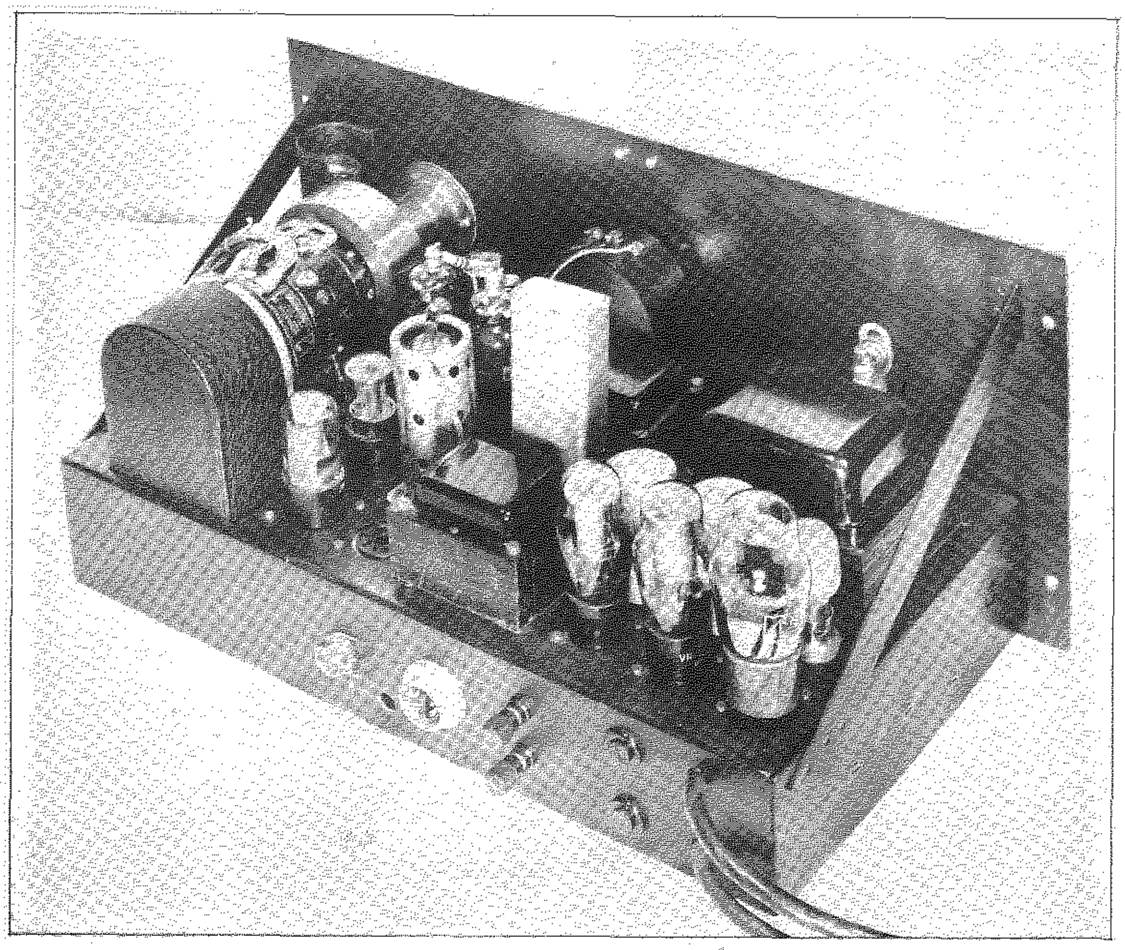
SLAVE VIBRATOR AND ELECTROMAGNETIC PICKUP

FIG. 5

FIG 6.



(A) PHOTOGRAPH OF INSTRUMENT AND AUXILIARY EQUIPMENT.



(B) REAR VIEW OF INSTRUMENT SHOWING LAYOUT OF COMPONENTS

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