CALIBRATION OF A SIMPLE EDDY CURRENT ERGOMETER

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1. Introduction

The authors have developed recently a simple ergometer (1972) to meet the objectives of adaptability and low cost. Called the Ergowheel*, as shown in Fig. 1, it consists basically of a disc with calibrated braking device and transmission system to allow rotation of the disc by the subject. One way of achieving this rotation is by connection of the chain transmission of any conventional bicycle to the chain transmission of the Ergowheel, enabling the subject to perform work under measurable conditions, Fig. 2.

Fig. 1. The Ergowheel

The work load is imposed by the apparatus while the rotating disc, made from electrically conductive material, rotates between the poles of an adjustable horseshoe-shaped permanent magnet. The heating problems identified by Clark and Greenleaf (1971) for a mains-operated eddy-current ergometer were avoided by attaching the disc of the Ergowheel to a cycle wheel and by not encasing it. The spokes of the rotating wheel cause currents of air to flow over the disc and magnet, giving adequate cooling.

Fig. 2. The Ergowheel used with cycle drive.

Variations in the velocity of the disc or in the position of the magnet relative to the disc alter the work load imposed on the subject. With the velocity of the disc displayed on a speedometer connected to the Ergowheel transmission and a calibration of the magnet linkage system for various positions of the magnet, the physical work being done by the subject can be measured. A calibration method is described.

2. Method

2.1 Principle of Calibration

When a force acts on an object in such a way as to make it rotate about an axis at right angles to the plane containing the force, the product of the force and its radial distance from the axis of rotation is known as the torque, or twisting moment. The power absorbed expresses the time-rate at which energy is imparted to the object, and for a rotating object is expressed as $\text{Power} = \text{Torque} \times \text{Angular Velocity}$, where $\text{Angular Velocity} = 2\pi N$ (N being the number of revolutions of the object per unit time).

As shown in Fig. 3, mechanical braking by a pair of semi-circular shoes round a rotating circular drum results in a Torque, T_1 , which tends to rotate the shoes with the drum. By extension of one of the brake shoes to form an arm to support a weight, the Torque, T_1 , can be counter-balanced by the Torque, T_2 . With the system balanced about A, the common axis of rotation, and a weight support arm of known length r , the Torque, T_2 , can be determined from the weight required on the

*Worthwhile Designs Ltd., 26 Grange Road, Eccles, Manchester. Patent No. 1279201

Fig. 3. Diagram of a typical simple mechanical brake.

Fig. 4. Transmission system between electric motor and mechanical brake.

support arm to maintain the balance. Further, knowing the angular velocity of the rotating drum, the power absorbed by the system can be calculated using the previously mentioned formula, $\text{Power} = \text{Torque} \times \text{Angular Velocity}$. To obviate the need to account for the weight of the support arm itself in this formula, the second brake shoe can be extended as a counterbalance.

The measurement of the revolution speed of the drum, from which can be calculated its angular velocity, can be done using a stroboscope and electronic counter/timer, cf, for example, Clark and Greenleaf (1971). Without such equipment, it was found adequate to measure the time for 200 revolutions of the drum to 0.1 sec, with a calibrated 3 sec sweep stopwatch. With a mechanical trigger connected to the drum and striking a contact once per revolution, the time for the 200 revolutions was approximately 42 sec. Over such a time span, error in duplicate measures was slight, as discussed below.

With a watt-meter connected to the power supply of the electric motor used to rotate the drum, as shown in Fig. 4, it is possible to construct a graph showing watt-meter readings as a function of the power absorbed by the mechanical brake for various weights on the support arm. Having gained this information, the

mechanical brake can be replaced by the ergometer and, with known ergometer disc velocity, the magnet position can be adjusted until the required power to be absorbed by the ergometer, as shown by the appropriate watt-meter reading, is obtained. A diagram of the main components of the calibration system is shown in Fig. 5.

2.2 Detail

2.2.1 Calculation of the power absorbed by the mechanical brake W(MB).

If X = time in sec for 200 revs of the drum, then the speed of revolution (N) = $\frac{200}{X}$ revs per sec.

If the weight on the weight arm is y lb and the length of the weight arm (as in Fig. 3) is r ft, then the power absorbed by the mechanical brake is given by

$$W(\text{MB}) = \text{Torque} \times \text{Angular Velocity},$$

When yr equals Torque and $2\pi N$ equals Angular Velocity,

$$\text{then } W(\text{MB}) = yr 2\pi N$$

Fig. 5. Plan view showing arrangement of main components in the calibration of the Ergometer.

$$= \text{yr } \frac{2\pi 200}{X} \text{ ft lb/sec.}$$

$$\text{i.e. } W(\text{MB}) = \frac{2\pi 200}{500} \frac{746}{X} \text{ yr watts}$$

$$(\text{i.e. } \frac{2\pi 200}{550} \frac{\text{yr}}{X} \text{ horse power})$$

and if the weight arm $r = 1$ ft then

$$W(\text{MB}) = 1704 \frac{Y}{X} \text{ watts.}$$

Ideally, the Ergowheel would be calibrated at its 'standard' speed (i.e. one equivalent to using a bicycle having a driving chain wheel of 48T and pedalled at 90 rpm). In practice, however, two things prevent this, i) the impracticability of providing the exact reduction gearing from the electric motor to the Ergowheel, and ii) changes in motor speed when under load. Therefore, we state:

2.2.2 Calculation of the Power Absorbed by the Ergowheel W(E) at 'Standard' Speed for Magnet Positions Determined from Power Absorbed by the Mechanical Brake W(MB) at Slightly Different Speeds.

- (i) The Ergowheel is geared from the bicycle $\frac{48}{18} \times \frac{48}{16}$ and at the 'standard'

calibration speed of 90 pedal rpm this gives an Ergowheel disc speed =

$$\frac{48 \times 48}{18 \times 16} \times 90 \text{ rpm}$$

$$= 720 \text{ rpm.}$$

- (ii) The Ergowheel disc was geared from the mechanical brake countershaft (C), Fig. 5, $\frac{16 \times 48}{18 \times 16}$

Thus, at 720 rpm of the Ergowheel disc, the countershaft should turn at

$$\frac{18 \times 16}{16 \times 48} \times 720 \text{ rpm}$$

$$= 270 \text{ rpm.}$$

- (iii) If, for any reason the revolution speed of the countershaft (C) differs from that shown in (ii) above, a correction factor must be applied to the formula $W(\text{MB}) = 1704 \frac{Y}{X}$. This will allow

calculation of the power absorbed by

the Ergowheel at that magnet position if it were to be run at the 'standard' speed.

As the power absorbed by an eddy current braking system under the condition applicable to the Ergowheel varies in proportion to the square of the speed of the disc, the correction factor is calculated by

$$CF = \frac{\text{Theoretical spd of countershaft (C)}^2}{\text{Actual speed of countershaft (C)}}$$

If, as before, cf 2.2.1., the speed of the countershaft is calculated from the time in sec to complete 200 revolutions, the correction factor becomes

$$CF = 270^2 \div \frac{200^2 \times 60^2}{X^2}$$

$$= \frac{270^2 \times X^2}{200 \times 60^2}$$

- (iv) Thus the power absorbed by the Ergowheel W(E) for a particular magnet position and 'standard' disc speed, calculated from the force required to achieve balance on the mechanical brake and the actual revolution speed of the countershaft, is

$$W(E) = 1704 \frac{Y}{X} \times \frac{270^2 \times X^2}{200^2 \times 60^2}$$

$$= 0.8626 X Y.$$

2.2.3 Procedure

A mains operated 1 hp single phase 50 c/s induction electric motor, 'no load' speed 1425 rpm (A.E.I. Ltd.)* was used with a 2" diameter V-pulley on the drive shaft to drive the system. Such motors run at rated speed in 'no-load' conditions. With load, speed alters and this has to be taken into account as described in 2.2.2 above. The problem could be overcome by the use of a synchronous motor and pin-table gearing, but to obtain the necessary power output the increase in cost and size in comparison to the induction motor would be considerable. The developing field of reluctance motors still limits also by the low power outputs available. The power for the motor was transmitted to the brake drum via a V-belt to a 10" diameter V-pulley on the countershaft (C), as shown in Fig. 4. The Polytetrafluorethylene (PTFE) brake shoes were

*G.E.C. Power Engineering, Trafford Park, Manchester, 17.

tightened against the brake drum using the two wing nuts shown in Fig. 3. The countershaft, running in self-lubricating bearings, was mounted on an angle-iron frame bolted to a solid wooden base. The power taken by the electric motor was measured using a Sangamo Weston Watt Meter Model S67, range 0 - 750 W, calibrated to ± 1.87 watts full scale deflection. The calibration run comprised the following steps:—

- A. 1. Ten minutes warm-up of the electric motor and the mechanical brake.
2. Set free-running load of the system to 210 W shown on the watt meter by obtaining the correct transmission belt tension. Use this as a check (K_1) on the constancy of the free system load.
3. Measure the time for 200 revs of the countershaft.
4. Put a 1 lb weight on the brake shoe arm, tighten the brake shoe until the arm is balanced and horizontal. Record the reading on the watt-meter and the time for 200 revs of the countershaft. Remove the weight and release the brake to free running. Check that the free running load (K_1) is still 210 W, ± 2 W. If not, repeat procedure from A.2 until such constancy of the free system load before and after braking is obtained.
5. Repeat A.2 to A.4 with weights 2 lb to 13 lb inclusive.
6. Calculate $W(E)$ as shown above 2.2.2 and construct a graph using watt meter readings WMR v calculated $W(E)$. (See specimen results, Fig. 6).

Fig. 6. The curve of Ergowheel power demand, from Prony brake calculations, on motor power output.

- B. 1. Connect the Ergowheel by chain transmission to the sprocket on the countershaft and bolt securely to the base of the rig.
2. With the magnet pole faces clear of the Ergowheel disc, start the electric motor and allow the system to warm up for ten minutes.
3. With the magnet fully clear, record the free running load of the Ergowheel shown on the watt meter. Use this as a check (K_2) on the constancy of the Ergowheel and transmission system during calibration.
4. Read from the graph constructed, as described in Section A.6., the required watt meter reading $W(MR)$ for $W(E) = 100$ W and advance the magnet so that some of the disc is moving between the poles of the magnet until the required $W(MR)$ reading is achieved on the watt meter. Mark the appropriate point on the calibration scale on the Ergowheel. Wind the magnet fully clear of the disc and check that K_2 is constant ± 2 W. If not, repeat B, after first establishing the constancy of K_1 as above.
5. Repeat B.4 for $W(E) = 150$ W to 500 W inclusive.
6. Switch off the power supply to the electric motor, disconnect the Ergowheel and restart the motor and transmission drive.

After two minutes, again check K_1 is constant as above.

Note. It is not necessary to check the time for 200 revs of the countershaft during B. as a given load on the electric motor, whether by mechanical brake or Ergowheel, results in a given countershaft speed and thus the information on revolution rates obtained in A. is sufficient.

3. Specimen Results

Fig. 6 describes data obtained using the procedure shown above. For each weight balanced on the mechanical brake arm, the time for 200 revolutions of the countershaft and a watt meter reading were recorded and, following 2.2. above, the power absorbed for the Ergowheel driven via an appropriately geared system (see above) at the 'standard' speed was calculated.

From this data the curve of power absorbed by the Ergowheel versus watt meter reading was drawn, as

shown in the figure. The Ergowheel may then be calibrated, as described above, with particular calibration points (e.g. E(W) 100, 150, 200, etc.) being determined by reading from the graph the appropriate watt meter readings to be elicited.

Fig. 7. Relationship between Ergowheel calibration scale reading and true power output for various chainwheel sizes and a pedalling rate of 90 revs per minute.

Such calibration refers to the use of the Ergowheel driven by a 48 toothed cycle wheel transmission. For different gearings from alternative sized cycle chain wheels, a factor has to be applied to this calibration to state the correct power demand of the apparatus. Fig. 7 shows calibration curves to make such adjustments for cycle chain wheels in the size range 46 to 56 toothed.

4. Discussion

Some variability exists in the procedure described. Repeated calibrations have indicated that applying a t statistic at the 5% level of significance the confidence limits for this variability stated as W(E) range from ± 2.75 W to ± 4.82 W, which represents a % error of approximately 1 to 2½%.

Control in calibration is important. There are identifiable sources of error. Most important of these sources is the mechanical state of the transmission systems involved. From a practical viewpoint, this may

be divided into sections, viz. 1. the drive from the electric motor to the mechanical brake, 2. the transmission through the brake shoe to the weight support arm, 3. the drive from the countershaft to the Ergowheel, 4. the Ergowheel transmission, and 5. the bicycle used in experiments. Section 5 falls outside the scope of the present paper, but good mechanical maintenance clearly is important. Sections 1, 3 and 4 involve obtaining correct alignments of belts and chains, secure pulleys, lubricated bearings and a stable test bed to which the rig is attached. Section 2 involves the problem of 'stick-slip' which occurs in any mechanical braking system. The use of a PTFE brake lining instead of a motorcycle brake-shoe lining eased this problem considerably and soaking the brake shoe in oil also improved stability. However, care should be taken to ensure that the brake shoes do not become overheated, as toxic gas is given off when PTFE is heated above 750°C. (It is wise not to smoke, particularly where there is likely to be PTFE dust in the atmosphere, as the hot cigarette decomposes it too!)

Other less significant sources of error are the electric motor and the timing procedure used. The variability in the watt meter readings from the motor creates a band of 2 to 3 W within which readings have to be estimated, suggesting a confidence range for the determined values of approximately ± 1.5 W. Measuring the speed of revolution of the countershaft by the method described also involves error. Timing to 0.1 sec as described results in an error bound at the Ergowheel of approximately ± 0.01 W(E) with a weight on the mechanical brake support arm of 1 lb, to ± 1.21 W(E) at 14 lb weight. With assessment of the replicability by repeated timings, the maximum range of the timing data, from any one of the loads, provided a confidence interval equivalent to ± 1.8 W. Both sources of error are small in comparison to those that can be elicited from transmission problems.

5. Conclusion

The procedure described provides a comparatively simple, accurate and inexpensive way of calibrating an ergometer.

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