A Wide-Band Double-Vane Torque-Operated Wattmeter for 3-CM Microwaves*

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Summary—This paper describes a torque-operated wattmeter for waveguide, capable of measuring power in the range of 10 to 200 watts in the wavelength range 3.05–3.45 cm, with an accuracy of about 2 per cent over most of the wave band.

The instrument is an absolute standard since its calibration depends only on measurements of mass, length, and time. Negligible power is absorbed, and the instrument is insensitive to mismatch.

INTRODUCTION

In an earlier paper[1] a torque-operated wattmeter for 3-cm microwaves has been described, and it has been shown that an accuracy of about $1\frac{1}{2}$ per cent can be obtained with the instrument when working into an accurately matched load.

The present instrument has been designed to operate satisfactorily over a wider band of frequencies, and in addition its sensitivity to mismatch is greatly reduced.

CONSTRUCTION

The general arrangement of the instrument is shown in Figs. 1 and 2. The wattmeter consists essentially of a short vertical section A of waveguide, connected by E-plane bends to horizontal input and output sections, and containing a movable element. The latter consists of a glass tube B to which two thin metal vanes are attached. The vanes are separated by one quarter guide wavelength at the midband frequency. A small mirror fixed to the lower end of the glass tube is used in conjunction with a lamp and scale to indicate the angular position of the movable element.

The movement carries also a locking cone used to clamp the suspension by means of the lever E, when the instrument is not in use. The lower end of the suspension dips into a dashpot containing silicone oil, thus ensuring "dead-beat" response.

The movement is suspended by a 15-micron-diameter quartz fiber C from a vertical shaft D.

The shaft D is held by a collet in the extension mounted in the center of the shaft of the driven wheel of the worm gearing associated with a slow motion drive.

Two dials and a vernier indicate the angular position of the shaft D.

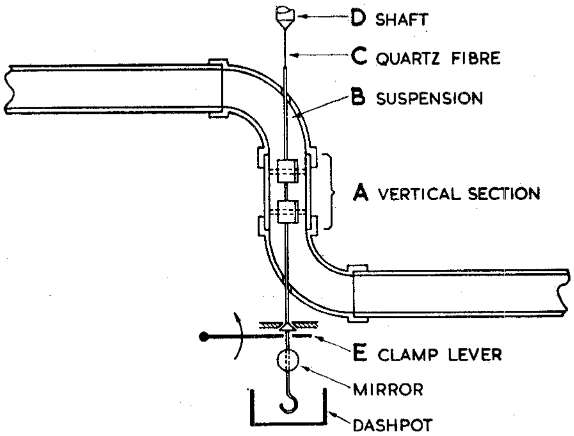

Fig. 1—Construction of the wattmeter.

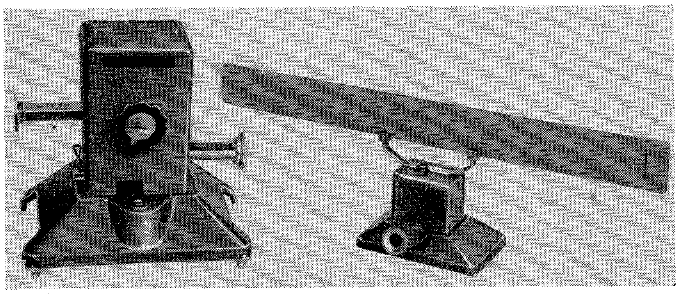

Fig. 2—X-Band wattmeter and scale.

The ends of the horizontal guides are blocked with half guide wavelengths of expanded polythene to screen the vanes from draughts. The base of the wattmeter rests on three leveling screws, and a spirit level is built into the base.

PRINCIPLE OF OPERATION

When microwave power flows through the waveguide, the associated electric field produces a torque tending to rotate the vanes into line with the unperturbed electric field. The torque produced is proportional to the square of the electric field strength magnitude, and hence to the power flow. The resulting deflection of the movement is compensated by turning the torsion head. The angle through which the torsion head must be returned to restore the vane to its initial position is therefore a measure of the microwave power.

A transmission line analog shown in Fig. 3 is helpful in understanding the action of the instrument. Each vane acts like an electrostatic voltmeter connected across a transmission line. The inductive diaphragms

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[1] A. L. Cullen and I. M. Stephenson, "A torque-operated wattmeter for 3 cm microwaves," *Proc. IEE*, vol. 99, pt. 4, p. 294; July, 1952.

shown in Fig. 1 are equivalent to inductances shunted across the electrostatic voltmeters and so chosen as to cancel their capacitive reactances so that the resultant impedance of each shunt is infinite. There is then no discontinuity in the line.

When the load into which the wattmeter works is matched, the relationship between torque and power can be written

$$T = KP. \tag{1}$$

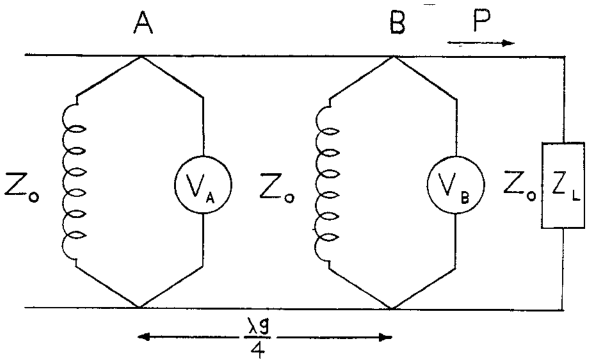

Fig. 3—Equivalent circuit of wattmeter.

When the load is not matched, a correction factor must be introduced into this equation to allow for the effect of mismatch. The mismatch correction factor is easily deduced with reference to Fig. 3. Suppose that there is a voltage minimum at B. The impedance at such a point will be $Z_0 \cdot s$, where s is the voltage standing-wave ratio $(V_{\min}/V_{\max})$, and the square of the rms voltage at this point will be $V_B^2 = PZ_0 \cdot s$ where P is the net power flow. Because of the quarter-wave separation between A and B, there will be a voltage maximum at A and the square of the voltage at A will be $V_A^2 = PZ_0/s$. In the actual wattmeter, the total torque is equal to the sum of the torques on the individual vanes, that is, to $V_A^2 + V_B^2$ in the analog. Hence, the torque is given by

$$T = \frac{1}{2}\left(s + \frac{1}{s}\right)KP. \tag{2}$$

The constant K is the electrical calibration constant introduced in (1).

Thus, the mismatch correction factor is

$$F = \frac{1}{2}\left(s + \frac{1}{s}\right). \tag{3}$$

A fuller analysis shows that this factor is valid for any position of the standing-wave pattern. Since $F \geq 1$, the sensitivity of the instrument is increased slightly by mismatch. If $s > 0.9$ the increase is less than $\frac{1}{2}$ per cent.

A single-vane wattmeter may be in error by as much as ±10 per cent under the same conditions depending on the position of the standing-wave pattern, if no mismatch correction is made.

The correction factor

$$\frac{1}{2}\left(s + \frac{1}{s}\right)$$

for the double-vane instrument is strictly valid only at the design wavelength. At other wavelengths the mismatch correction becomes

$$\frac{1}{2}\left(\frac{1}{s} + s\right) \pm \frac{1}{2}\left(\frac{1}{s} - s\right) \cos\phi \cos\beta l. \tag{4}$$

In this expression ϕ is the phase angle of the reflection coefficient of the load which determines the position of the standing wave relative to the vanes, β is the waveguide phase constant $2\pi/\lambda g$, and l is the separation between the centers of the vanes. If, as is often the case, the position of the standing-wave pattern is not known the mismatch correction is uncertain. The limiting values of the mismatch correction factor are

$$\frac{1}{2}\left(\frac{1}{s} + s\right) \pm \frac{1}{2}\left(\frac{1}{s} - s\right) \cos\beta l. \tag{5}$$

The percentage error arising from the second term of (5) depends on the wavelength and on the standing-wave ratio. At 3.3 cm, for example, there is a possible error of ±1 per cent if $s = 0.9$, or $\pm\frac{1}{2}$ per cent if $s = 0.95$, the design wavelength being 3.20 cm.

CALIBRATION

The calibration of the instrument involves two separate stages.

The first stage is the electrical calibration in which the constant K is determined. This constant is equal to the torque per unit power for a matched load. The second stage is the mechanical calibration in which the angular deflection of the movement per unit torque is obtained.

Electrical Calibration

The electrical calibration is obtained from measurements made with a low-power waveguide test bench.

The calibration procedure and its theoretical basis have been dealt with in detail elsewhere[2] and it is beyond the scope of the present paper to do more than to draw attention to the following points:

1) The procedure is still valid if magnetic as well as electrical fields make a significant contribution to the torque.
2) Only length (and angle) measurements are involved. No electrical power standards of any kind are involved.
3) Any mismatch introduced by the wattmeter in the input guide does not affect the calibration though for functional reasons such mismatch is kept as small as possible.

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[2] A. L. Cullen, "A general method for the absolute measurements of microwave power," *Proc. IEE*, vol. 99, pt. 4, p. 112; February, 1952.

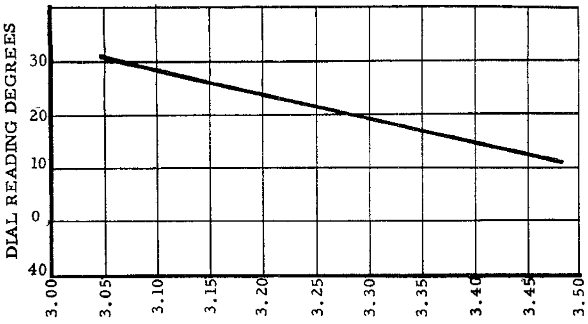

Fig. 4—Matching angle vs wavelength.

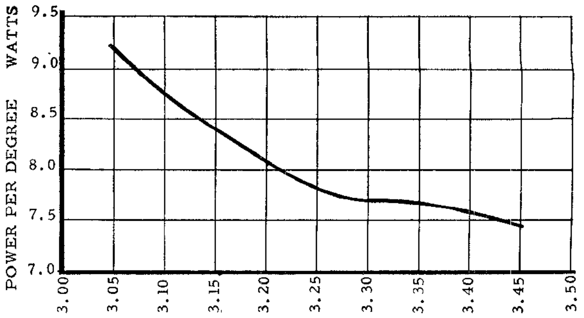

Fig. 5—Power calibration

4) The constant K is a function of θ, the angular position of the movement and of wavelength.

The calibration procedure must be carried out at a sufficient number of wavelengths in the wave band required to enable a smooth curve of K against λ to be drawn.

The optimum value of θ for best match (the matching angle) is also plotted as a function of wavelength.

Mechanical Calibration

The mechanical calibration consists essentially in determining the specific couple of the quartz fiber suspension. This is done most conveniently by timing torsional oscillations when several rods of known moments of inertia are attached in turn to the movement. If k is the specific couple, the static deflection θ_0 of the movement under the influence of a steady torque T is given by

$$\theta_0 = \frac{T}{k} \cdot \tag{6}$$

This is also the angle through which the torsion head must be turned to restore the movement to its initial position.

The determination of k has involved measurements of mass, length, and time only. Once again, no measurement of power is involved.

Over-All Calibration

Combining (1) and (6), we have the following relationship between torsion-head rotation and power when the load is matched:

$$P = K'\theta_0 \tag{7}$$

where $K' = k/K$.

Eq. (7) is the basic equation of the instrument. The constant K' has the dimensions watts/degree if the angle θ_0 is measured in degrees.

Typical Calibration

Two experimentally determined curves are required for using the double-vane wattmeter. The first is a plot of matching angle against wavelength and for a typical instrument takes the form shown in Fig. 4.

The second curve gives the power per degree as a function of wavelength and for the same instrument has the form shown in Fig. 5.

The calibration is carried out individually for each instrument.

The errors do not exceed 0.4 per cent for mechanical calibration and 0.25 per cent for electrical calibration.

SPECIFICATION AND PERFORMANCE

The wattmeter will measure power in the range of 10–200 watts. If the source is pulsed, it will measure mean power but the peak power should not exceed about 50 kw.

The mismatch produced by the wattmeter is small, not falling below 0.9 in the band 3.05–3.45 cm. The power lost in the instrument is around 2.5 per cent; it stays relatively constant over the band (to within 0.2 per cent) and compares with about 1.5 per cent loss of power in the same length of normal guide. When making precise measurements this loss has to be taken into consideration as shown later in comparison measurements against a water calorimeter.

The over-all accuracy of the wattmeter is as follows:

in the band	3.10	to 3.35 cm	±2 per cent
	3.05	to 3.10 cm	±3 per cent
	3.35	to 3.45 cm	±3 per cent.

COMPARISON WITH WATER CALORIMETER

Tests have been carried out in which the power of a cw magnetron was measured simultaneously by the torque-vane wattmeter and by a water-calorimeter wattmeter, the latter acting as a termination.

The comparison was carried out at a wavelength of 3.26 cm, the magnetron being capable of maximum output of 10 watts. A continuous flow water calorimeter was used, consisting of a thin pyrex-glass tube extending across the waveguide at a narrow angle in a plane parallel to the broad face. The power was measured in terms of the equivalent mains-frequency power required in an auxiliary heater coil to produce a rise in temperature (about 0.5°C) identical with that due to microwave power.

Two sets of readings were taken as follows:

1) With the wattmeter connected directly to the calorimeter with $s = 0.92$.

2) With the wattmeter connected to the calorimeter via a matching unit with $s=0.99$.

The readings of the two instruments for powers in the range 8–10 watts are given in Table I.

TABLE I

Comparison of Torque-Vane Wattmeter and Water Calorimeter

Torque-Vane Wattmeter	Water Calorimeter	Per Cent Difference
1) $s=0.92$		
9.02 watts	8.89 watts	+1.46
8.94	8.84	+1.13
9.65	9.48	+1.80
9.17	8.85	+3.60
9.10	8.84	+2.94
9.19	9 06	+1.44
Average difference between the two instruments 2.1 per cent.		
2) $s=0.99$		
9.10 watts	8.97 watts	+1.4
9.02	8.92	+1.1
8.98	8.85	+1.5
9.34	9.33	+0.1
8.94	8.87	+0.8
9.02	8.82	+2.3
Average difference between the two instruments 1.2 per cent.		

These results have been corrected to allow for the measured attenuation in the connecting waveguide. Furthermore, in case 1) above, the wattmeter readings have been corrected for mismatch using (3), and in case 2) above the small loss of power in the matching transformer has been taken into account.

Since the attenuation through the double-vane wattmeter was 2.4 per cent (measured value) a figure of 1.2 per cent was used in estimating the power loss between the vanes and the output flange. All corrections have been applied to the readings of the two wattmeters in such a way that the corrected power measured by each is referred to the output flange of the double-vane wattmeter.

The accuracy claimed for the continuous flow water calorimeter was ±1.5 per cent and that for the double-vane torque-operated wattmeter was ±2 per cent at 3.26 cm.

Conclusion

The work described in this paper shows that the initial aim of designing a wide-band torque-operated microwave wattmeter has been achieved. The accuracy claimed has been verified by comparison with the best water calorimeter wattmeter available.

The instrument is an absolute standard of power in the microwave band.

Acknowledgment

The authors wish to express their gratitude to Prof. H. M. Barlow for placing at their disposal laboratory facilities of the Electrical Engineering Department of University College, London, in the early stages of development, and for his interest and encouragement in the work. They thank members of the staff of the Wayne-Kerr Laboratories for help in the design of the instrument. Also, they are grateful to the Director of the Radio Research Station of the Department of Scientific and Industrial Research for providing facilities for comparison of the double-vane wattmeter with a water calorimeter wattmeter and to J. Lane for his invaluable assistance in this part of the work. Finally, author S. Okamura is indebted to the British Council for a scholarship which made his part in the work possible.

Traveling-Wave Resonators*

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Summary—**In the first part of the paper, the principles are given which have led to the conception of the traveling-wave resonator, and the calculations enabling its operation to be understood are presented.**

The second part describes the apparatus in detail and examines it, bearing in mind its use as high-power testing equipment.

Part I—Principle of Operation

Introduction

The testing of the power-handling capacity of a microwave transmitter and associated circuit, at far more severe conditions than the nominal ones, has always been considered a very difficult problem for which no valuable solution had been found until the present time.

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