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‘Aether drag’ in a transversely moving medium

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A previous measurement of the Fresnel ‘aether drag’ in a transversely moving medium (Jones 1972) has been repeated with improved accuracy to find whether the original Fresnel formula should be modified by a dispersion term as was shown by Lorentz and Zeeman for the longitudinal drag. A formula derived by M. A. Player and by G. L. Rogers gives the transverse displacement of a beam of light passing through a medium of thickness t moving with transverse velocity v as $vt(n_g - n_\phi^{-1})/c$ rather than $vt(n_\phi - n_\phi^{-1})/c$ as given by the original Fresnel formula, where n_ϕ is the phase refractive index and n_g is the ‘group refractive index.’ The present experiment gives results in accordance with the Player–Rogers formula rather than with the Fresnel formula or one in which the group refractive index alone is involved; it parallels what Zeeman found for the longitudinal case. The main improvement in experimental accuracy has come from recognition of errors in the method of calibration by optical micrometry.

1. INTRODUCTION

An earlier paper in the *Proceedings* (Jones 1972) reported the observation of Fresnel ‘aether drag’ in a transversely moving medium, and confirmed that the transverse deflexion δ of a beam of light passing through a medium of thickness t and refractive index n moving with velocity v transversely to the light is, to the first order,

$$\delta = vt(1 - n^{-2})/u,$$

where u is the velocity of light in the medium. This may be rewritten

$$\delta = vt(n - n^{-1})/c.$$

The question arises of whether u is to be taken as the wave velocity or as the group velocity, and whether n is the phase refractive index or the ‘group refractive index’ (i.e. the ratio of the group velocity in vacuo to the group velocity in the medium).

The question has some historical interest, for it is one on which Rayleigh changed his mind. He had originally (1881) concluded that, in contrast to other methods of determining the velocity of light, the determination by using transverse aether drag (stellar aberration) should give the wave velocity: but after being challenged by Ehrenfest (1910) Rayleigh subsequently decided (1911) that transverse aether drag methods, too, should give the group velocity.

My earlier determination of the transverse drag came close to the result to be expected from wave velocity. The internal consistency of 37 measurements (1.5 % s.d.) led to a standard error in the mean result of 0.25 %, which was well inside the difference to be expected from wave and group velocities (2.9 %) for the glass used (Chance 524589), and it seemed unlikely that any of the recognized systematic errors would bridge the difference. However, as a result of discussions with Professor G. L. Rogers, it was decided to repeat the experiment with a glass (Schott SF4) in which the difference between wave and group velocities was greater, and where unrecognized systematic errors would be less important.

Before the new experiment could be performed, Dr M. Player suggested from relativistic arguments that both phase and group velocities were involved so that instead of

$$\delta_{\phi} = vt(n_{\phi} - n_{\phi}^{-1})/c, \quad (1)$$

or

$$\delta_g = vt(n_g - n_g^{-1})/c, \quad (2)$$

where n_{ϕ} is the phase refractive index and n_g the group refractive index, the deflexion should be

$$\delta_n = vt(n_g - n_{\phi}^{-1})/c. \quad (3)$$

Rogers independently derived the same expression by applying Abbe image theory to the optics of the original experiment. The physical point in his treatment is that the detection of the aether drag is effected by observing the transverse displacement of an image formed by light which has passed through the moving medium, and for this image to be produced diffraction spectra of the object must be involved; and the light in these spectra must travel somewhat obliquely through the medium even if that in the zero order is travelling perpendicularly. The medium then necessarily has a component of motion along or against the direction of propagation of light in these spectra, and so this light will be subjected to a component of longitudinal aether drag of the magnitude concluded theoretically by Lorentz (1895) and observed by Zeeman (1914). Taking the resultant phase shifts in the diffracted spectra into account, Rogers concluded that the transverse displacement of the image should be as given in (3). The derivations by Player (1975) and Rogers (1975) are given in the preceding two papers.

The present paper describes a repetition of the 1972 experiment, with the accuracy improved so that it should be possible to discriminate between the values of deflexion to be expected from formulae (1), (2), and (3), and from which it appears that the Player–Rogers formula is confirmed.

2. INTENDED IMPROVEMENTS

The method used in the improved experiment is basically that of the original experiment, which was to pass a beam of light through a rotating disk of glass, parallel to the axis, and to measure the transverse displacement of the beam resulting from its passage through the disk. To reduce as far as possible the incidental displacement of the beam due to the changing figure of the disk caused by centrifugal

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force, and to any wandering of its axis of rotation with speed, the same precautions are taken as in the original experiment (Jones 1972) the description of which should be consulted for the principles of measurement employed. In addition, various refinements have been made in an attempt to discriminate between the predictions of formulae (1), (2) and (3) above.

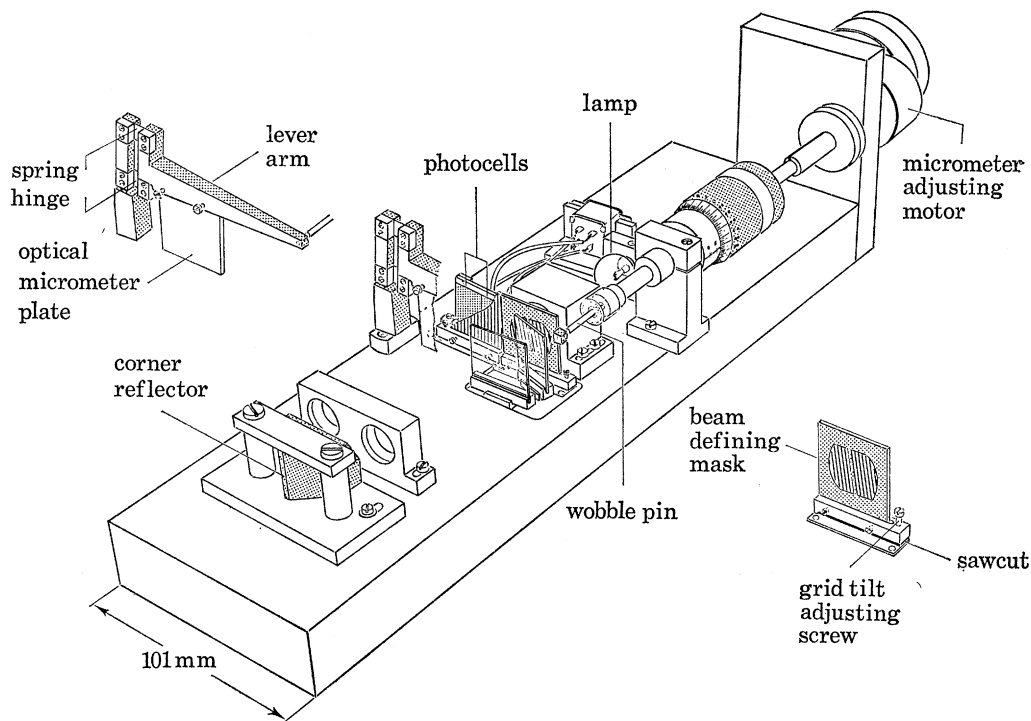


FIGURE 1. Optical displacement measuring system. The components that have been modified since the original experiment (Jones 1972) are shown shaded.

One of the optical measuring systems, as slightly modified for the present experiment, is shown at figure 1 and the complete assembly at figure 2; for ease of comparison with the corresponding figures (3 and 4) of the original paper, the more important modifications are shown shaded. As before, there are two optical measuring systems at opposite edges of the disk, and each optical system passes its beam of light twice through the disk, the second passage being effected by reversal of direction in a corner reflector. The outputs of the two measuring systems are combined in such a sense as to provide a self-cancelling system for errors arising from disk wobble, while summing the displacements that arise from the aether drag.

Choice of glass

The first step in improving the discrimination of the experiment was to find a glass with a high enough dispersion. Schott type SF4 (755276) was selected; it

was expected to give about 3.8% difference between formulae (1) and (3) and a further 1.2% between (3) and (2). In common with other high dispersion glasses it has a high density (4.78), and so the mass of the disk (300 mm diameter with an 80 mm diameter central hole and 23.23 mm thickness) is about 7.3 kg compared with about 3.9 kg for the original 524589 disk.

The extra mass entailed the drawbacks of increased inertia and increased weight. The greater inertia required either a greater time for running up to and down

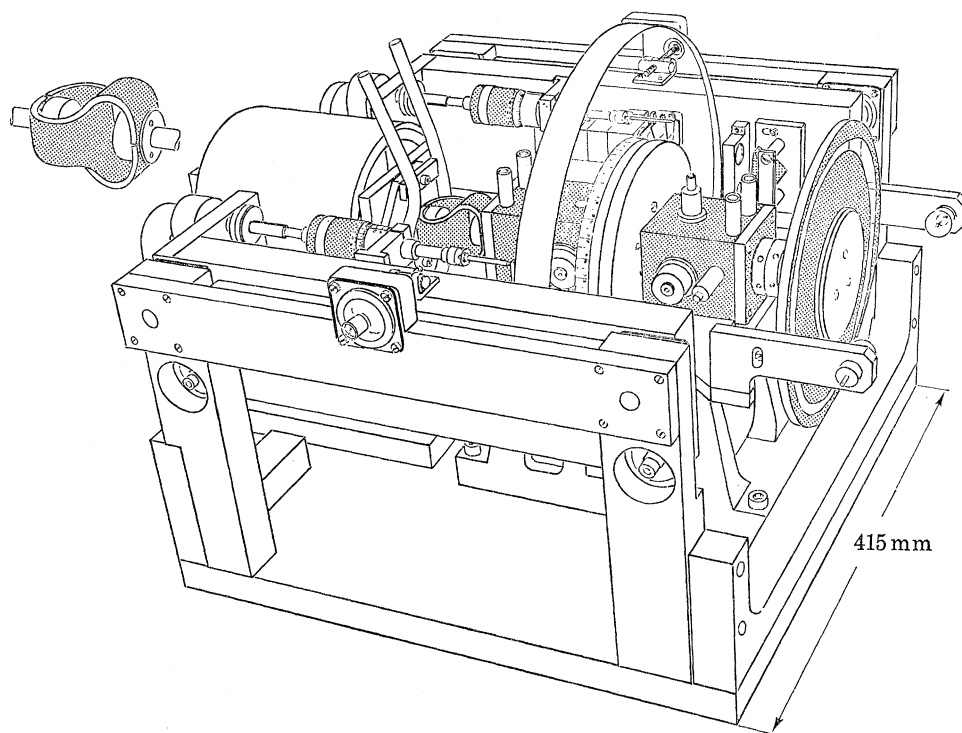


FIGURE 2. Complete optical and mechanical assembly. The components that have been modified since the original experiment (Jones 1972) are shown shaded. Inset: flexible coupling between motor and main shaft.

from speed, increasing the effects of any accidental drift of zero by prolonging the time necessary for an observation, or it required increased torque in the driving motor, with the risk of correspondingly greater mechanical distortion of the base. The greater weight resulted in more friction in the bearings with a consequent greater generation of heat which in turn could result in greater axis drift, as both the shaft and the bearings expand. Since one of the intended improvements was to increase the length of runs to about 45 min to allow some 20 successive readings to be taken, as compared with 10 min in the original experiment, the axial drift problems were now much more acute.

Coupling design

To reduce the effects of any misalignment between the driving motor axis and the disk axis a more flexible coupling was used. The design of this coupling is shown in figure 2: it is simply made by cutting a cruciform pattern in neoprene sheeting and bending the arms of the cross and fixing them to two bosses so as to simulate a figure 8 with the bottom rotated through 90° relative to the top. This coupling is very flexible in all degrees of freedom except that of rotation about the axis of the bosses; and it reduced any mechanical distortions of the base to an undetectable level.

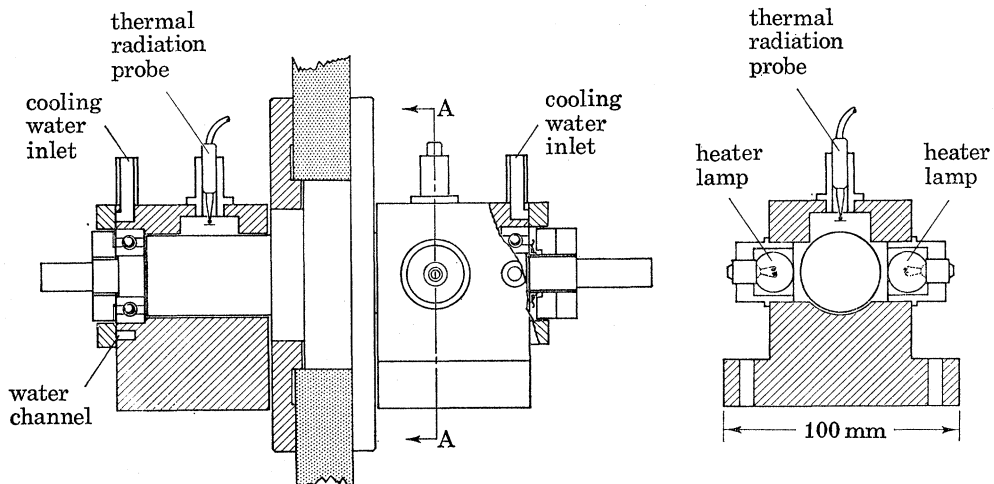


FIGURE 3. Scale diagram of main shaft and journals. Left: side view; right: section of AA.

Shaft and mounting

To reduce the drift of axis with speed (and especially with change of direction of rotation) due to play in the ball-races, the distance between the races was increased from 60 to 170 mm. A photoelectric monitoring device, which may be described elsewhere, was built to observe the drift of axis with speed and time. It showed that with the increased separation the bearings (Barden type 203FF3G/6) were sufficiently good to keep the drift with speed to below one arc second over the range $+1500$ to -1500 rev/min, but that drifts of several arc seconds occurred with time. These were due to heating of the journals and the shaft by friction in the ball-races, resulting in a mechanical displacement of the disk relative to the optical measuring systems which in turn produced appreciable effects on the apparent zeros of the optical displacement records. Journals and shafts had therefore to be controlled to as constant temperatures as possible. The journals were water-cooled, and the incoming water temperature was regulated by an immersion heater element controlled by a thermistor probe inserted into one of the journals. The shaft could not be water-cooled, and so its temperature was monitored by painting it black, and detecting the thermal radiation from it by another thermistor probe, which in turn

controlled the temperature of four small lamps inserted into the journals and which heated the shaft by radiation. As the frictional heating developed, the heating due to the lamps was reduced so as to regulate the temperature of the shaft. With these precautions, thermal drifts could be sufficiently limited to permit runs that typically lasted for 45 min. The shaft and journal layout is shown at figure 3.

Transverse velocity determination

The effective transverse velocity of the glass is taken as the product of the angular velocity of the disk, which is measured by a lamp and photocell counter-timer, and the mean radial distance of the axes of the traversing light beams from the axis of rotation. The beam cross sections are approximately circles of 11 mm diameter; and the positions of the optical systems are adjusted so that all four beams are equally spaced from the axis of rotation to within 0.25 mm.

Since the 'aether drag' on a beam passing through the disk is directly proportional to its distance r from the axis of rotation, and since a precision of the order of 1 in 10^3 is required, the previous visual estimation of the effective radius r is no longer sufficient. A jig was therefore made to fit over the shaft carrying the disk, and to support pieces of photographic film so as to interpose these in the light beams, so that the positions of the beams could be recorded and measured; trials showed that the use of this device enabled the positions of the beams to be established relative to the axis of rotation to about one part in two thousand.

Refractive index determination

The use of tungsten lamps as sources of light, and of silicon photocells as detectors, entails the problem of evaluating the effective mean wavelength of the light as assessed by the photocells, and hence of the refractive indices to be inserted in the displacement formulae, since both lamps and photocells 'peak' in the infrared. In the earlier paper, it had been assumed (correctly as it transpires) that the phase refractive index was unlikely to be less than 0.4 % less than the value at 589.3 nm; but now it was necessary to be more precise, and the effective value of phase refractive index was therefore found directly by a subsidiary experiment as follows:

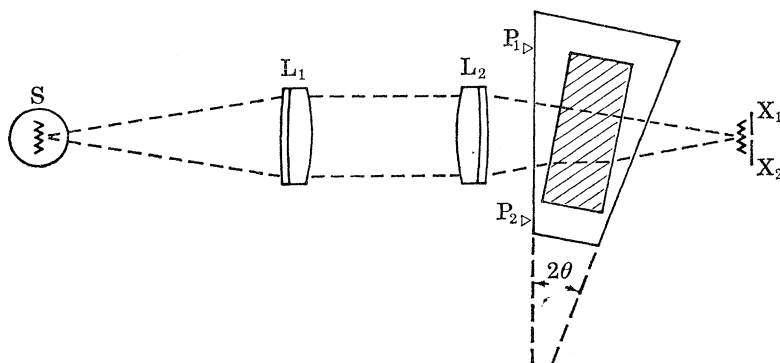


FIGURE 4. Arrangement for determining the effective refractive index of the glass disk.

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The lamp S (figure 4), the lenses L_1 and L_2 and the photocells X_1 and X_2 are all similar to their counterparts in the main experiment. The filament of S is at the principal focus of L_1 ; and X_1 and X_2 are so placed in the principal focal plane of L_2 that the image of the filament falls equally on X_1 and X_2 . Either the main glass disk itself or a sample of the same glass (shown shaded) is now interposed between L_2 and X_1 - X_2 at a small angle θ so as to produce a transverse displacement of the filament image. This displacement is measured by mounting X_1 - X_2 on a parallel spring micrometer movement, and adjusting the micrometer so that the image falls equally on X_1 and X_2 as indicated by the balancing of their outputs; this can be done easily to $0.1 \mu\text{m}$. The measurement is then repeated with the disk or sample turned to an equal angle on the other side of the optical axis. This can conveniently be done by mounting the specimen on a wedge-shaped plate which can be located against two stops P_1 and P_2 situated so that P_1P_2 is normal to the optical axis. After the location of the image has been determined with the specimen in one position, the wedge is turned through 180° and the new location of the image determined. The effective angle through which the specimen has been rotated (2θ) is equal to the angle between the faces of the wedge. Even if the faces of the sample are not exactly parallel, any prismatic effect can be eliminated by taking further readings with the sample rotated on the wedge through 180° about an axis normal to the plane of the diagram and passing through the optical axis. The effective refractive index can then be worked out from the formula

$$n^2 = \alpha^2 + (1 - \alpha^2) \alpha^2 t^2 (\alpha t - \epsilon)^{-2}, \quad (4)$$

where $\alpha = \sin \theta$, and 2ϵ is the transverse displacement of the image produced by rotation of the specimen. The beam can be made narrow enough by an aperture at L_1 for the angle of incidence not to vary by more than two degrees from one side of the beam to the other, and this is sufficient for the accuracy of refractive index measurement required (1 in 10^4). The result for SF4 glass was $n = 1.73907$, indicating from the known dispersion curve an effective mean wavelength of 760 nm. The method was tried on several other glasses, and all gave a value close to this figure; it was also confirmed by a computation by Dr M. A. Player from the known emission curve of the lamp and the response curve of the photocells.

The optical micrometer

The calibration procedure for establishing the absolute value of the observed deflexion depends on producing a small transverse displacement of the light beam by rotating a glass plate of known refractive index and thickness through a known angle. The effective refractive index can be measured by the method described in the preceding section. The angle of rotation has to be sufficiently large (about $400''$) to be measured with the necessary precision by an autocollimator; the latter in turn can be checked by reference to standard angle gauge blocks. The rotation is generated by a mechanical micrometer (figure 1) actuating an arm on spring strip hinges. Since the linear motion of the micrometer is about $200 \mu\text{m}$, if this is

to be repeated to within 1 in 10^3 , the micrometer adjustment must be repeated to $0.2 \mu\text{m}$. Larger drum micrometers were therefore substituted for the micrometers used in the original experiment; they were checked by a laser interferometer.

Care was at first taken to set the glass micrometer plates normal to the central axes of the light beams. The expression for the transverse displacement of a beam when its plate is then rotated through an angle θ is

$$\delta = \alpha t [1 - (1 - \alpha^2)^{\frac{1}{2}} / (n^2 - \alpha^2)^{\frac{1}{2}}], \quad (5)$$

where $\alpha = \sin \theta$, and which simplifies to

$$\delta = \theta t (1 - n^{-1})$$

for small values of θ .

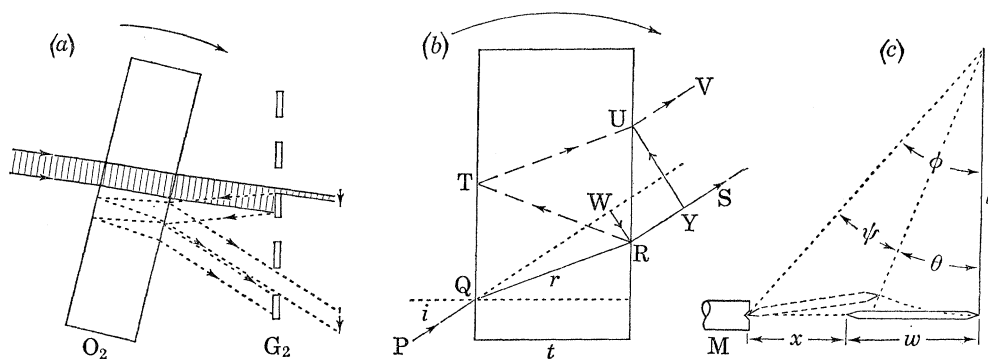


FIGURE 5. Errors arising in optical micrometry. (a) Reflexion of light at the surface of the analysing grid, with subsequent partial reflexion back to other parts of the grid by the surfaces of the optical micrometer plate. (b) The production of a secondary ray by partial reflexion at the surfaces of the optical micrometer plate. This ray, although much weaker than the original ray, moves at about three times its speed, and in the opposite direction as the optical micrometer plate is rotated. (c) Geometry of the mechanical linkage between the mechanical micrometer via the wobble pin to the lever arm of the optical micrometer.

With all the foregoing precautions taken, many runs were made to determine the magnitude of the aether drag; and these appeared to confirm the bias of the original experiment in favour of formula (1). But when the optical micrometer plates were turned a few degrees off normal, results began to fluctuate; and it was noticed that the aether drag deflexions were, surprisingly, more constant than the calibration deflexions produced by the optical micrometers.

Ultimately, the cause of the variable calibration deflexions was found to lie in stray reflexions at the surfaces of the micrometer plates and of the grids used in the optical measuring systems. This may be seen by considering a simplified version of the relevant details of the calibration system (figure 5a).

If G_2 is the analysing grid with photocells behind it and the optical micrometer plate O_2 in front, consider an image of one element of the object grid which is

formed in the plane of G_2 : part of the light in the image falls in a space of G_2 and the rest falls on an adjacent bar. If G_2 is made by depositing aluminium on glass (as was the case) the light that falls on the bar is reflected back into the optical system, and strikes the two surfaces of O_2 . If, in turn, these surfaces are partly reflecting they send some of the light back again to G_2 , and it will again fall partly on a space and partly on a bar in G_2 . The proportion of this light that gets through the space, and thus affects the photometric balance, will vary with the angle of inclination of O_2 , and will simulate a movement of a stray image across G_2 which may add or subtract from the genuine optical micrometer effect. (A rather similar argument applies if the optical micrometer plate, instead of being situated in front of the analysing grid, is placed in front of the object grid.) The extent to which the calibration is thereby falsified is not easy to calculate: if O_2 is of unbloomed glass the stray images will have about 8% of the intensity of the main image; their rate of translation as O_2 rotates is several times greater, but an offsetting factor is the extent to which the stray image is defocused by the extra path length. With these factors in mind, it is easy to accept that calibration errors of the order of 10% could be introduced and would be greater for thin plates than thick ones—it was in fact the use of particularly thin plates (0.34 mm) that drew attention to the source of the error, which was finally found by visual inspection.

The error remained undetected for some time because it could clearly not have existed if the surfaces of O_2 were non-reflecting. They had indeed been 'bloomed' for visible light, but this blooming proved ineffective in the 700–900 nm region. The errors were very much reduced when new plates were bloomed for this region; and they were reduced to an undetectable value when photographic grids were substituted for the bright aluminium grids previously used.

To confirm that the error had been eliminated, calibrations were made with the optical micrometer plate set over a range of angles up to 0.1 radian to the axis of the beam. The sideways displacement of the beam for a constant displacement (200 μm) of the mechanical micrometer then varies owing to two independent causes: first, the sideways displacement of the beam for a small rotation of the optical micrometer plate increases with the angle θ of inclination of the plate to the axis of the beam as given by (5), and secondly the angular displacement of the lever arm also increases with mechanical displacement of the micrometer, owing to the behaviour of the mechanical linkage. To evaluate this second effect, consider the geometry of figure 5c, where w represents the length of the wobble-pin, l the radius of the lever arm, and x the displacement of the mechanical micrometer M from its zero position when the angle between w and l is 90° and when M and w are collinear. From the geometry,

$$\theta = \phi - \psi = \arctan \frac{x+w}{l} \arccos \frac{(x+w)^2 + l^2 - w^2}{2l[(x+w)^2 + l^2]^{\frac{1}{2}}}.$$

In the linkage used, $l = 81.47$ mm, $w = 27$ mm and x ranged from 0 to 9 mm. As a result, the angular deflexion for a 200 μm change in x at $x = 8$ mm was about 1%

greater than that at $x = 0$; this was confirmed by direct measurement with an auto-collimator.

It is worth noting that a further calibration error can arise from the use of an unbloomed optical micrometer plate, as may be seen from figure 5*b*. Most of the incident beam PQ emerges at R parallel to its original direction, and displaced to one side by an amount $WR = t \sec r \cos(i - r)$. Part of the light is, however, internally reflected at R and after a further partial reflexion at T most of this energy emerges parallel to the original direction along UV. The transverse displacement of UV with respect to RS is $UY = 2t \tan r \cos i$. Thus for small angles of incidence i , RS is displaced to one side by an amount $it(1 - n^{-1})$ while UV is displaced from RS to the other side of the incident beam by an amount $2itn^{-1}$. If n is about 1.5, the transverse displacement of RS with respect to PQ is about $\frac{1}{3}it$, while the displacement of UV to the other side is approximately $\frac{4}{3}it$. If the reflexion coefficient at the glass/air interface is about 4%, then the ray along UV has about 0.16% of the energy of that along RS, and it is translated at about four times the transverse speed of RS as the micrometer plate is turned, and in the opposite direction. This is equivalent to reducing the calibrated displacement of RS by about 0.6%, and an appropriate correction must therefore be made. There is, of course, no need for such a correction if the micrometer plate is appropriately bloomed.

Electronics

One of the intentions of the present experiment was to improve the technique of compensating for variations of refractive index from point to point in the glass of the disk. This involved enlarging the size of the original subsidiary disk used to generate the compensation signal, which was recorded on this disk as a variable-width transparent track, illuminated by a small lamp and monitored by an auxiliary photocell. With the improved system it was possible to compensate for any minor differences in the responses of the two optical measuring systems to refractive index variations in the disk; and it was found possible to reduce the effect of these variations on the optical measuring systems to one-fortieth of their original value.

In the final experiment, however, this refinement was not needed because simultaneous improvements had been made in the electronic filter design which resulted in the effects of refractive index variations being smoothed out to the stage where there was no danger of their driving the amplifiers into nonlinearity. The variations were, of course, cyclic at the frequency of rotation of the disk, 25 Hz; the filter time constant was 3 s, and this proved sufficient to produce a disturbance-free record of the aether-drag displacement at all speeds above a few hertz.

3. MEASURING PROCEDURE

The two optical measuring systems were set up so as to have as identical performances as possible, as judged by the geometrical disposition and cross sections of the light beams, and so that their sensitivities, in terms of the signal developed by

the photocells for a given displacement of the final image, were matched within 5%. The two systems were then mounted in the assembly, and their positions adjusted so that the mean distances of the light beams from the axis of rotation were all equal within about 0.2%. The whole system was then evacuated, and allowed to settle down overnight.

At the beginning of a measuring run, the sensitivities of the two optical measuring systems with their associated amplifiers were adjusted to be within about 0.5% of one another, by making small adjustments in the voltages of their lamps, and the displacement sensitivities of the two systems determined by moving the optical micrometers through previously calibrated displacements. These operations were performed with the disk rotating at 1500 rev/min to simulate the operational conditions as closely as possible, and a run to measure the aether drag deflexions was then made by running at 1500 rev/min for about 20 s, followed by a deceleration and reversal to 1500 rev/min in the opposite sense. The cycle was then completed by a further deceleration and reversal to 1500 rev/min in the original sense, and the process repeated for about 20 reversals, the whole run taking about 40 min. The deflexions were recorded in the manner illustrated in figure 6 of the 1972 paper.

At the end of the run the calibration was checked by repeated displacements of the optical micrometers. These calibrations were made not at the full operating sensitivity of the electronic amplifiers, but at one fiftieth of that value, because the smallest optical micrometer displacements that could be made with the necessary accuracy (0.1%) were about fifty times the deflexions due to aether drag. The attenuation factor that had thus to be introduced into the electronic amplifiers was therefore determined to better than 0.1%; checks from time to time showed that it stayed constant to this value over the three months of the final experiment.

During each run the rotational speed of the disk was continuously monitored; again, it was typically constant to within 0.1% of the nominal value. At the end of each run the system was allowed to settle down to its original temperatures. On an average day about four runs were possible.

After the difficulties with the optical micrometer calibration had been identified, several series of runs were made between July and November 1974 with different optical micrometer plates, so as to check that the previous errors had been effectively eliminated. The plates used were (1) silica, thickness 2.004 mm, $n = 1.4542$, (2) silica, 0.3376 mm, (3) glass, 1.2806 mm, $n = 1.5119$, (4) glass, 0.925 mm, $n = 1.5055$, (5) glass, 0.7626 mm, $n = 1.5106$. In all cases the value of refractive index (n) quoted is that at 760 nm wavelength. The results from all micrometer plates were consistent; the most extensive series, that with the fifth plates, lasted from 4 October to 28 November; and it is reported in the following section.

4. RESULTS

The results for the series of 95 runs, each of which involved about 20 observations of the aether drag deflexions in reversing the speed of the disk from +1500 to

–1500 rev/min are shown as a scatter diagram in figure 6. The ordinates are the measured drag, calculated as a ratio of that to be expected from

$$\delta_h = vt(n_g - n_\phi^{-1})/c$$

and the abscissae display the date of each run. This form of display should reveal any systematic change with time, such as might result from increased play in the bearings if the error cancellation system were imperfect. In fact, no change due to wear in the bearings was detected, and so they were intentionally tightened and loosened as indicated in figure 6. The results were slightly more consistent after the bearings were tightened on 2 November, and were a little higher, on average, after the bearings were made very loose on 21 November.

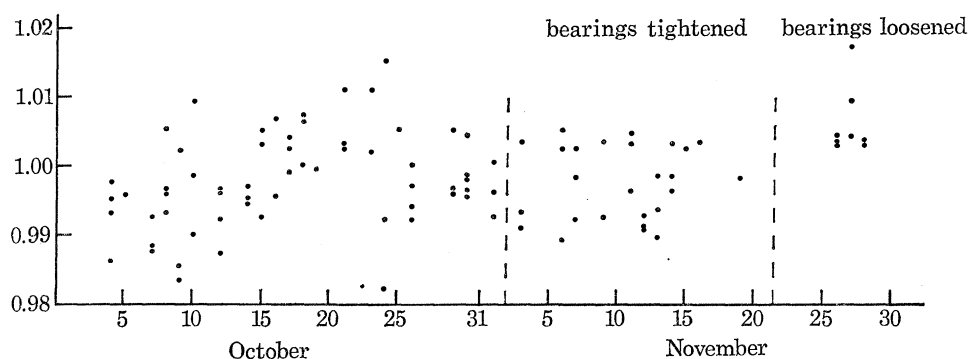


FIGURE 6. Scatter diagram of results of 95 consecutive runs in October and November 1974. Ordinate: aether drag deflexions expressed as fractions of that to be expected from the hybrid formula (3). Abscissa: dates of runs. Each point is the mean of a run of about 20 aether drag reversals, the typical s.d. for the mean being about 0.3%.

The results are also displayed as a scatter diagram in figure 7*a* but this time the abscissae are the mechanical micrometer deflexions in millimetres away from the positions where the optical micrometer plates are normal to the light beams. Since the lever arms were 81.47 mm, a mechanical displacement of 10 mm corresponds to an optical micrometer angle of 0.1227 rad. Figure 7*b* displays the increase in optical micrometer displacement with offset, due to the factors described in a preceding section and which had been applied in making the plots of figure 7*a*. Again, the results are consistent over the range of micrometer angles used, showing that the earlier calibration troubles had been eliminated.

Finally, the results are plotted as a histogram in figure 8, showing the scatter of results against the deflexions to be expected from the three formulae as follows in terms of the deflexion for aether drag to be expected from

$$\delta_h = vt(n_g - n_\phi^{-1})/c,$$

and which for the conditions of the experiment give

$$\delta_h = 8.028 \text{ nm},$$

$$\delta_\phi = 0.9617\delta_h,$$

$$\delta_g = 1.0123\delta_h.$$

The statistics of the 95 runs give a figure of $0.9986\delta_h$ with an error of $\pm 0.0007\delta_h$ s.d. in the mean, placing the 95% confidence limits at 0.9972 and 1.0000 relative to the deflexion to be expected from the hybrid formula.

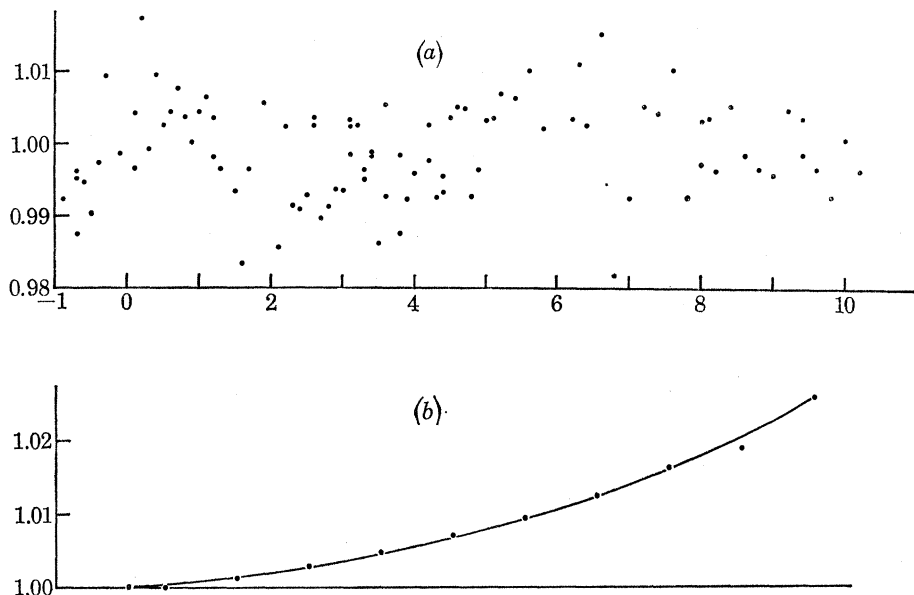


FIGURE 7. (a) Scatter diagram of 95 results for aether drag deflexions (ordinates) expressed in terms of that to be expected from the hybrid formula (3). Abscissae: displacement (mm) of mechanical micrometer away from its zero position when the optical micrometer plates are normal to the beams. (b) Correction curve, with same abscissae and ordinates, for non-linearity of optical micrometer displacement as mechanical micrometer is offset, which has been applied before plotting to figure 7 (a).

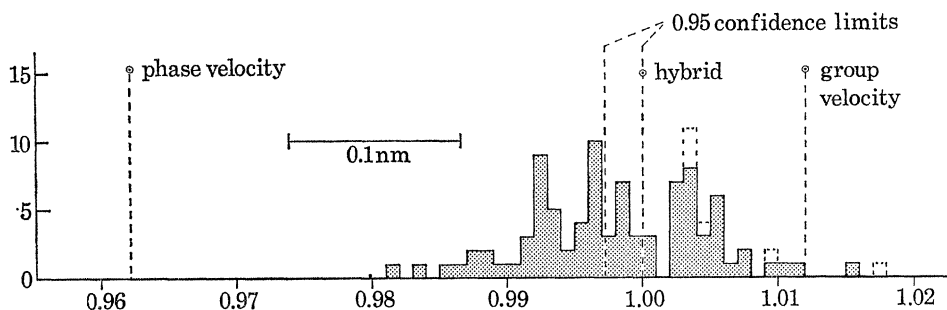


FIGURE 8. Histogram of results of 95 runs. Ordinate: number of results in measurement interval. Abscissae: values of aether drag deflexions expressed as fractions of that to be expected from hybrid formula (3). The results obtained after loosening the bearings on 21 November are unshaded.

It should be emphasized that these limits are merely those arising from the scatter of results, and that they take no account of any hidden systematic errors that may have occurred in measuring the various quantities involved in the determination.

Although effort has been made to remove systematic errors such as beset the optical micrometer calibration in the previous experiment, it is difficult to guarantee that all have been eliminated. Moreover, there are several random errors of order 0.1 % involved in the measurement procedure which, combined with the actual scatter of results, might produce a cumulative random error of 0.2–0.3 % s.d. And it must be remarked that the absolute difference in aether drag deflexions predicted by formulae (2) and (3) is no more than 0.1 nm.

Even so, the results are markedly in favour of the hybrid formula of Player and Rogers being correct, rather than the expressions involving wave refractive index or group refractive index alone. This parallels what Zeeman (1915) found for longitudinal aether drag. Whether the expression $(n_g - n_{\phi}^{-1})$ has an interpretation in physical terms any simpler than those of our three papers is so far obscure.

This investigation might not have been made without the original query from Professor G. L. Rogers; I have benefited from discussions with him and Dr M. A. Player, and also with Professor P. T. Landsberg. I am also grateful to Dr J. C. S. Richards for the necessary electronics, and to Dr W. J. Bates for making some of the optical micrometer plates. The mechanical construction was by Mr H. Barber, Mr L. Keith and Mr G. Paget; and most of the runs were made by Mr A. M. Gardner over some hundreds of hours of observation. The diagrams for this paper were prepared by Mr T. Wratten, Mr H. Sutherland, Mr G. Coull, and Mr J. Grant.

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Note added to proof, 19 June 1975. The longitudinal case for which Zeeman (1914) confirmed the same formula as this paper finds for the transverse case was that of the classical Fizeau experiment in which a fluid medium flows through tubes with fixed end windows. Einstein (1914 *Astra. Nachrichten* **199**, 8–10) also considered other longitudinal cases and pointed out that with a moving block of solid refracting medium if light is made to enter and leave the block from the side and is reflected inside the block by 45° mirrors (so that it travels the length of the block after the manner of the light path in a periscope) the dispersion term is absent and the original Fresnel formula holds.