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Physics. — "*The Propagation of Light in Moving Transparent Solid Substances. I. Apparatus for the Observation of the* FIZEAU-*Effect in Solid Substances.*" By Prof. P. ZEEMAN.

(Communicated in the meeting of May 3, 1919).

1. As a result of an experiment by ARAGO with a *glass* prism FRESNEL drew up his bold hypothesis on the convection coefficient in 1818. When in 1851 FIZEAU wanted to put FRESNEL's hypothesis to the test, he experimented, however, with *water*, and examined whether or not the velocity of light in standing water differs from that in moving water.

There are many reasons to be adduced for carrying out an experiment, so exceedingly difficult as that of FIZEAU, in the first place with water; it is, however, also interesting to examine the motion of light in *solid*, transparent, rapidly moving substances. In this connection experiments with rapidly moving quartz and glass have been made by Miss SNETHLAGE and myself. In this communication I will give the description of the apparatus with which these experiments have been made. It may be well to call attention to a few points referring to FIZEAU's experiment with water.

Let c be the velocity of light in vacuo, μ the index of refraction of the water, w the velocity of the water with respect to the tube in which it moves; then the velocity of propagation of the light with respect to the tube is according to FRESNEL:

$$\frac{c}{\mu} \pm \left(1 - \frac{1}{\mu^2}\right) w \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

In this the upper or the lower sign is to be taken according as the water and the light move in the same or in opposed directions.

In 1895 LORENTZ demonstrated that FRESNEL's convection coefficient in a dispersive medium must be replaced by:

$$1 - \frac{1}{\mu^2} - \frac{\lambda}{\mu} \frac{d\mu}{d\lambda}$$

This changes formula (1) into:

$$\frac{c}{\mu} \pm \left(1 - \frac{1}{\mu^2} - \frac{\lambda}{\mu} \frac{d\mu}{d\lambda}\right) w \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

The experiments made by FIZEAU in 1851, plead in favour of formula (1). MICHELSON and MORLEY's investigation of 1886, performed with MICHELSON's interferometer in one of the numerous forms into which as a real PROTEUS this wonderful instrument is capable of being changed, gave with white light a value of the convection coefficient which was in excellent agreement with the coefficient that follows for yellow sodium light from formula (1).

Experiments that have been carried out by me with different colours ranging from violet to red, and in which the axial velocity of water in the tube was directly measured have been communicated by me in different papers to this Academy [1]). The validity of the formula (2) with the term of dispersion could be demonstrated with an accuracy exceeding 0.5 $^0/_0$. The optical effect that is measured in these experiments, is a displacement of interference bands, which is given in parts of the distance of two bands by the formula:

$$\frac{4l}{\lambda\, .\, c}\left(1-\frac{1}{\mu^2}-\frac{\lambda}{\mu}\frac{d\mu}{d\lambda}\right)\mu^2 w, \quad . \ . \ . \ . \ . \ . \ . \quad (3)$$

in which l represents the length of the whole liquid column which is in motion.

2. The apparatus that has been used for the investigation of the motion of light in solid substances, is shown diagrammatically in

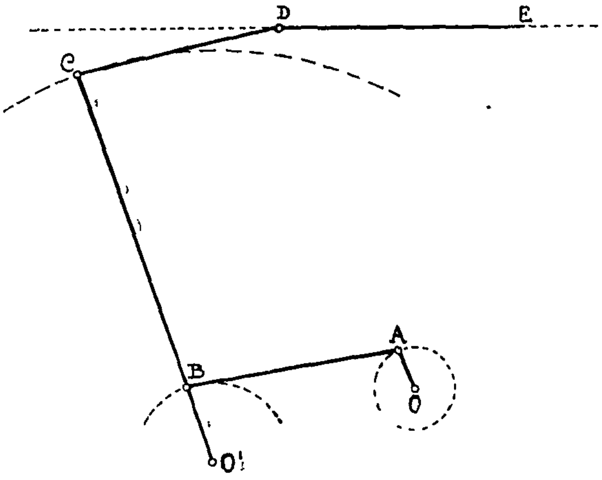

Fig. 1.

fig. 1 on a scale of $^1/_{20}$, and might also be used with simple modifications for the investigation of costly liquids and compressed gases.

The moving, transparent substance is rigidly connected with a piece DE, and can therefore rapidly move to and fro parallel to

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[1]) ZEEMAN, These Proc. **17**, 445, 1914; **18**, 398, 1915; **18**, 711, 1915; **18**, 1240, 1916; **19**, 125, 1916.

the dotted line, while a beam of light traverses the substance parallel to *DE.*

The piece *DE* is moved to and fro, as it is coupled with the rods *DC* and *O'C*. Normal to the plane of the drawing, axes have been fixed at *O* and *O'* in a very strongly constructed frame, on which the bed is fastened, along which *DE* moves. The axis in *O* is rotated by a 3 H.P. motor, so that point *A* describes a circle; *B*, connected with *A* by the rod *AB*, acquires a movement backward and forward, which is transferred to *C* enlarged.

The piece *DE* of fig. 1 is shown diagrammatically in fig. 2 seen from above on a scale of $\frac{1}{10}$. In *A* and *B* there are bronze shoes which can slide along steel guides. All these have been constructed with great care, so that a rectilinear, horizontal motion of the shoes can be obtained. The rods of the transparent substance, which rest on a wooden block which is connected with 4 screws to *A* and *B*, participate in this motion.

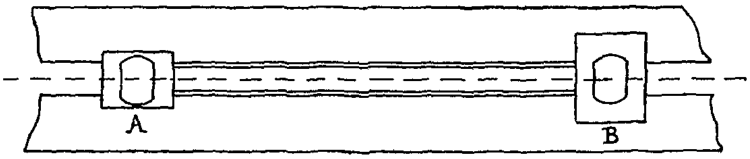

Fig. 2.

The Plate, which is annexed to this communication, gives a general survey of the apparatus. The thickness of the guides amounts to 9 mm., the width to 70 mm., the length to 1.84 m. They rest on heavy rectangularly bent pieces, which constitute the sides of the bed, and which for greater firmness are connected by very solid pieces about half a meter long, which are bent twice rectangularly. These pieces are arranged on the lefthand at the bottom side, on the righthand on the upper side of the bed, as is to be seen in the Plate. The entire length of the upper part of the apparatus is 2.30 m., the length of the stroke is about 1 meter.

In order to ensure the regular movement of the apparatus it appeared to be necessary to provide it with two fly-wheels, a large one seen in the foreground, and a smaller one fastened on the other side of the axis of rotation, and just visible on the Plate The whole apparatus it fastened with solid bolts to a granite slab, cemented to the large pillar of the laboratory.

As appears from a consideration of fig. 1, the rate of motion of the shoe is variable, with two, slightly differing maxima of velocity, one in going, and one in returning along the guides. The maximum velocity is practically constant over a distance of about 20 cm. When the fly-wheel performs 184 revolutions a minute, the maximum velocity rises to somewhat more than 10 meters per second. This is the highest value that can be reached.

The driving apparatus was constructed by the works Werkspoor at Amsterdam. The execution of the mechanical parts had to be adapted to the optical requirements in the Laboratory.

With regard to the optical arrangement of the experiment we may refer to my former communications on the FIZEAU-effect. The quickly moving transparent, solid substance takes the place of the running water of the earlier experiments. The length of the moving column of quartz or glass ranged between 100 and 140 cm. in different experiments. After the successive application of numerous improvements it was possible to cause the beams of light to interfere through the moving quartz or glass, and to obtain pure interference lines at the greatest velocity which the apparatus admits.

The experiment comes to this, that the interference bands are photographed twice, first with a movement of the column to the right, and then with a movement to the left. These photos should be taken by admitting light during a time of the order of one hundredth of a second and at the moment of the maximum velocity.

The optical effect to be expected, when l represents the length of the moving transparent substance is:

$$\frac{4l}{\lambda \, . \, c}\left(\frac{1}{\mu}-\frac{1}{\mu^2}-\frac{\lambda}{\mu^2}\frac{d\mu}{d\lambda}\right)\mu^2 w \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

It appears from this formula, which will be proved later on (see II), that the optical effect is approximately proportional to $\mu-1$. In FIZEAU's experiment the optical effect is proportional to μ^2-1 according to (3). This difference is connected with the fact that in FIZEAU's experiment in its usual form, the velocity in a definite point of space is always the same, whereas in the experiment now considered the light must overtake the moving bar.

As regards the optical effect observed, the method considered now will accordingly be two and a half times less favourable for a value of $\mu = 1,5$ than FIZEAU's usual method, because $\frac{\mu^2-1}{\mu-1} = \mu + 1$. This is more or less compensated by an advantage with regard to the dispersion term. As follows from formulae (3) and (4), the ratio of the dispersion term to the principal term is in the second case 1,6 times that in the former experiment.

We shall now discuss a few more particulars of the arrangement and the use of the apparatus.

3. *Determination of velocity.* In order to get an insight into the course of the velocity in the movement along the guides the position of DE (see fig. 1) was determined corresponding with 16 different, equidistant positions of the fly-wheel. The graph indicating the connection between the positions of the fly-wheel and the deviations, has about the shape of a sinusoid, but the two halves of the curve are not symmetrical, and in particular, the course of the graph in the neighbourhood of the two boundary values is not exactly the same, as already appears from a consideration of fig. 1, when A is imagined to move along the dotted circle.

The velocity-time curve can be graphically derived from the path-time curve. At the maxima the velocity is practically constant over a distance of 20 cm., of which only 10 cm. are used. As was already stated the maximum velocity amounts to $1000 \frac{\text{cm.}}{\text{sec.}}$ for 184 revolutions per minute, and proportionally the calculated velocity can be derived for another number of revolutions. Whether really the maximum velocity should be taken into account in the calculation, depends further also on the position of the moving column at the moment that the shutter, before the objective of the telescope, transmits light. In some cases this position did not correspond to that of the maximum velocity, which circumstance was of course taken into account in the interpretation of the photos.

In the most accurate experiments the maximum velocity of the column was directly measured (for the method used see one of the following communications), which renders us independent of the supposition that the fly-wheel possesses a constant angular velocity.

It appeared in the experiments that the machine ran more uniformly when the fly-wheel rotates clockwise (seen from the side of the larger fly-wheel) than in the opposite direction. Of course this favourable direction was always used.

4. *Shutter.* Only at the moment that the machine has its greatest velocity may the light be admitted to the photographic plate. The following arrangement was made for this purpose. The axis of the fly-wheel is provided with a toothed wheel, which engages with a second toothed wheel with double the number of teeth. An insulated brass ring with cams is fitted on each side of this second wheel. The cams on the two rings are placed

diametrically opposite one another so that they take each other's places as regards level after every whole revolution of the fly-wheel, and can make contact with a suitably fixed sliding contact.

By means of the cam an electric current is closed in a circuit containing also windings of a coil that acts electromagnetically on a shutter or light interrupter. When the second cam makes contact, the current passes through a second coil, which closes the shutter. Every time the fly-wheel, and consequently the moving column, have arrived at the *same position* and move *in the same direction*, the shutter is opened, and light is allowed to pass for a moment. The intensity of the interference figure not being strong enough to give a satisfactory photo with light that has been admitted once, a photo is taken e.g. thirty times successively on the same plate. As the light is let through three times a second, this takes only ten seconds.

To take the second photo, i.e. when the column of quartz moves in the opposite sense, a duplicate arrangement is used, placed symmetrically with respect to the one sketched. By means of a double-pole throw-switch it becomes possible to make one series of photos succeed the other immediately without loss of time and without stopping the machine. Only the photographic plate must be moved a little. The two large toothed wheels, and between them the small one can be distinguished on the Plate near the bearing at the bottom on the righthand side.

As some time passes between the moment that contact is effected by the cam and the opening of the shutter, this time must be taken into account. To do so it is necessary to perform a phase determination.

5. *Phase determination*, i.e. to ascertain by a separate experiment, if really at the moment of the greatest velocity the light passes through the shutter. For this purpose the shutter is put at the place of the greatest velocity by the side of the bed. The wooden beam containing the transparent substance, is provided with a black screen with an opening. A glowlamp is placed in the line: shutter-place of the greatest velocity, a line which is normal to the longitudinal direction of the apparatus. When the machine is running and when the shutter is in action, the lamp must be observed through it. When it does not work at the right moment, the field of view remains dark. Then the phase can be improved, and can at last be made accurate by gradually shifting the large toothed wheel with respect to the small one. This causes the contact to be formed at another moment.

6. *Observation and Photography of the Interference-bands.* The shutter is placed before the objective of the telescope, which was also used before to record the FIZEAU-effect[1]). In the focal plane of the telescope, which is provided with a negative achromatic system of lenses to increase the effective focal distance, a system of wires has been placed, which is photographed at the same time with the interference bands.

The position of the interference fringes with respect to the wires is determined. Immediately behind the wires the photographic plate is in a plateholder mounted quite independently of the telescope with the cross wires. The photographic plate can be put in the required position without the telescope being touched, and be shifted to take the successive photos.

The telescope, the plate-holder, the interferometer, and the glass rectangular prism, in which the interfering beams are reversed, are mounted on separate freestone piers, which are cemented to the large pier. This last mentioned prism, which also served in the earlier experiments, is visible on the righthand side of the Plate.

7. *Measurement of the time that the shutter or interrupter is opened.* This time, which is of the order of 1 or 2 hundredths of a second, is dependent on the current in the coils of the circuit of the interrupter and can be regulated by this and by the change of the width of the opening in the moving screen of the interrupter. For the determination of the time the interrupter is placed before the lens of a camera, with which a small lamp is photographed, which revolves on a disk with known velocity. During the time that the interrupter is opened, the lamp describes part of a circle, the length of which is measured.

8. *Checking and regulating of the apparatus.* After the interference fringes have been made as distinct as possible, the beams passing only through the air, a compensator is placed in one beam, consisting of a plane parallel glass plate 7 m.m. thick and with a diameter of 25 m.m., made by Hilger. This plate can be rotated round a vertical and horizontal axis, and enables us to change the slope and the distance of the interference fringes in a simple way. In many cases it was unnecessary to insert this compensator, as the desired interference fringes were already obtained with the interferometer alone. Then the column of quartz and glass

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[1]) Cf. ZEEMAN. These Proc. **18**, 400, 1915.

is introduced into the beam of light, precautions being taken which will be mentioned in communication II. It must then first of all be ascertained whether the apparatus and particularly the guides satisfy the high requirements on which the efficacy of the whole arrangement depends.

With a slow movement of the shoes with the quartz column along the guides the interference fringes did not remain stationary, but changed with regard to distance and slope. When the apparatus had first been put together, this movement of the bands was very great. It is clear that it must also occur for a perfectly homogeneous column bounded by parallel planes, when the movement does not take place along a perfectly straight line. For then the whole column of a length of more than 100 cm. acts as a compensator of exceedingly great thickness. In order to make the circumstances as favourable as possible the steel plates of the guides were laid on the supporting plates about in the correct position. The bolts which were used to keep the apparatus in place, are then screwed down till a sensitive level, which could be placed in longitudinal and in transverse direction, indicated a plane as much as possible horizontal, determined by the upper planes of the steel guides. It was then examined if the inner edges of the guides were as perfectly straight and parallel as possible, and improvements were made in this respect by filing and grinding. At last the free play of the bronze shoes in their movement along the guides was removed as much as possible. Great improvements were successively made to the apparatus in this direction, so that rotation and change of distance of the fringes became comparatively slight. It was, however, impossible to have the interference fringes quite steady when the apparatus was slowly moved. This is, however, not necessary; what is required after all is that the same positions of the interference bands are found again when the shoes have returned to the same point of the guides. The results prove that this is actually the case, and that the occasional deviations fall now in one sense, now in another.

The excellent definition of the interference fringes, recorded with the quickly moving apparatus in itself proves already, that every time about the same position of the bands is obtained, as 20 or 30 images are superposed (see above § 4), which could never produce a definite image, when the single light impressions were not almost identical. Sometimes the system of fringes proved to be rotated, and then the photo had to be rejected. Of course care had also to be taken that the guides were well oiled, and there is one more *dynamic particularity* that had to be seen to. When the motor has been started for the first time, then the apparatus hardly ever gains the maximum velocity, which corresponds to 184 revolutions of the fly-wheel per minute. It gives the impression that the apparatus is hampered by a resistance, e.g. only 140 revolutions are made. The starting is then repeated a few times, and at the third or fourth attempt the machine suddenly runs very smoothly without jerking. Then the feeling of uneasiness of the operator at the exceedingly rapid motion of the large apparatus so close to the delicate optical parts of the interferometer, has abated somewhat and the experiment can begin. ¹)

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¹) The experiment is not entirely without danger. When the experiment with glass was to begin, four beautifully finished glass cylinders 20 cm. long and 2.5 cm. thick were placed in the wooden shoe, and optically adjusted. In the very first experiment with this glass column one of the glass cylinders, which evidently had not been properly fastened, got loose, while the apparatus moved at full speed; it smashed all the other pieces and knocked the brass end pieces off the shoe. The glass cylinders were entirely smashed, the work of months was destroyed. It was a wonder that the interferometer and the glass rectangular prisms remained undamaged.

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