Repeating the Harress-Sagnac Experiment

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In his thesis (1911) F. Harress[2] reported the results of his experiments concerning the propagation of light within a rotating vitreous body. A similar experiment has been carried out two years later by Sagnac[3] using air instead of glass as the propagation medium. The theory of the experiment published by Harress has been corrected by P.Harzer[4] and A.Einstein[5] respectively and the theory of both experiments has been correlated to those of Fizeau and Zeeman and exposed together by M. von Laue[6]. Based on these theoretical corrections, O.Knopf[7] has re-examined the results of Harress.

The theoretical basis is extremely simple: Two coherent light bundles are allowed to circulate in opposite directions in the periphery of a closed polygon filled with an arbitrary medium, being fixed to and resting within the coordinate system of the earth. After having run through the closed circuit once, both light bundles are brought to interference. The resulting position of the interference stripes with respect to a reticle is called "zero position". If the polygon rotates with angular velocity ω about an axis enclosed by the light circuit and if the projection area perpendicular to the rotation axis of the polygon is F, then the interference stripes will shift during rotation away from their zero position by an amount measured in units of the width of the stripes equal

$$\Delta = 4\omega F/\lambda c \qquad (1)$$

where λ is the wavelength and c the velocity of light as measured in the vacuum. It must be mentioned that formula (1) is, firstly, almost independent from the influence of accelerations as shown by W. Wien with reference to general relativity theory and, secondly, is independent from the medium in which the light propagates.

In his measuring experiments Harress made rotate his device with an angular velocity of up to 750 rpm; thereby Δ equalled roughly 0.2. Therefore, a shift of the stripes equal 2Δ = ~0.4 was obtained between left and right hand rotating directions. Sagnac used a maximal velocity of 120 rpm. Thereby 2Δ equalled ~ 0.07. It is difficult to estimate the accuracy of Sagnac's measurements, because the results of only 4 measurements were reported. Anyway, the device rotated slowly, such that the effect was indeed small. As a source he used the white light of a small electric lamp. He determined the wavelength entering in formula (1) by comparing the width of the interference stripes obtained with the electric lamp while the device was resting with those obtained with a Hg-line. As to the stability of his device he uttered in the section: "Précautions à prendre" as follows: « Cette orientation (of the moving interference stripes) diffère de l'orientation relative au repos et on a trouvé utile de dérégler d'avance légèrement de facon que les franges soient un peu inclinées dans le sens convenable quand le plateau est au repos. Les franges se redressent quand le plateau tourne et deviennent verticales pour une fréquence convenable.»

The singular measurements of Δ by Harress differed from each other by 10 to 18%. Therefore, Sirs M. von Laue and M. Wien suggested to repeat the experiment. Financial support was provided by the "Notgemeinschaft" (partnership of emergency), but mostly by Zeiss Ld, where the devices were constructed and the experiments conducted.

Fig. 1

In order to throw into bold relief all aspects which have been taken into account with our reconstruction, I wish to spend a few words about the original device of Harress. The

horizontal design of the device can be seen in Fig. 1. Light ran around along the prisms P1-P10. It was entered and separated into two coherent bundles starting off from the middle of the prismal arrangement. The bundles, as seen in direction of the arrows a and b, are depicted in Figs. 2a and 2b. The interferences were set and their width and orientation adjusted using the adjusting prism $P_{i,}$ which could be made revolve around a fixed point by means of three screws. Light entered in horizontal direction during one revolution only at two azimuthal sites of the device, as shown by the arrows b and b'. Having travelled once through the prismal circuit, both coherent bundles were brought together again within the semi-reflecting silver layer of the apparatus and left the device in coaxial direction to reach the photodetector. The aperture of the device comprised about ¼ degree. Thus, during one revolution in time T, light left the device only during 1/720 T to reach the detector. The light for interference was therefore very weak so that a light arc, filtered by coloured glasses, had to be operated. As already mentioned, Harress reached an angular velocity of 750 rpm. With higher velocities interference patterns became blurred.
In Sagnacs device, both, the light source –a small lamp- and the photographic camera were taking part in the rotation.
In repeating Harress experiments I tried, while keeping the area of the interferometer unchanged, to increase the angular velocity so as to reach a value for 2Δ near 1. This required in case of Harress device 1600 rpm. However, as Harress observed, interference patterns blurred away above 750 rpm. Two reasons could account for this effect: first, vibrations of the apparatus, unlinked to the resting camera, at higher rotational speed, and, second, displacements of the light reflecting prisms caused by centrifugal forces. To avoid these influences, it has been proposed to construct the apparatus with a floating shaft and fill up the interior with a liquid of equal density as the prisms, thereby eliminating centrifugal forces. Of course, the critical rotational speed of the floating axis-shaft had to be well below the intended velocity of 1600 rpm. In addition, I wished to use monochromatic light. Since a quartz-quicksilver-arc-lamp could hardly be incorporated into the device, I chose light from a resting light source entering the apparatus coaxially, i.e. continuously and allowed the photographic camera, as Sagnac did, take part with the rotation. The optical device of the interferometer was, in the first instance, identical with Harress apparatus. The photographic camera was mounted on the top (Fig. 3). Coherent light entered the apparatus along the dotted line. Interference patterns developed within the focal plane F of the tray T. Thereon a platelet of glass with graved measuring marks was fixed. Interference patterns were projected along with the measuring marks through a planar lens M (focal distance 2 cm) to the photographic plate L. Because of the filling with liquid there was no total reflection at the outer surface of the prisms P_1-P_{10} (Fig. 1) and it was necessary, therefore, to silver those areas. The liquid used for filling had to be clear, of density 3.2 and shouldn't corrode the silvering and the inner wall of the apparatus (consisting of Siemens-Martin steel) as well as the parts of aluminium in its interior. I have been advised to use an aqueous solution of cadmium-boro-wolframate. This solution however turned out to be of no use because, immediately, it spilled out again from the filling mouth. Apparently gases had formed in the apparatus, which drove the liquid out. The liquid was therefore removed and, instead, the prisms fixed with strong screws to the outer board of the apparatus using intermediate rubber stoppers. Finally, the apparatus weighed about 80 kgs and was mounted on a vertical axis of 16 mm thickness, extending approximately 50 cm beyond the upper end of the guiding shaft. The turbine drive was connected to the inferior end of the axis. The whole thing was then fit into a block of concrete weighing 4 tons and sheltered in the cellar of the "skyscraper" of Zeisswerke.

The topmost story housed the water tank. The water pressure in the cellar achieved 4.5 atmospheres. To measure the rotational speed, a chronograph was used, which registered every hundredth revolution of the machine along with the second signals of the astral time

clock of the Zeiss-observatory. The critical angular velocity of the machine came to be at about 600 rpm. With 1600 rpm the machine rotated perfectly, the transit through the critical angular velocity, however, caused violent concussions such that the optical device got destroyed. In order to avoid this, I tried to install steel reflectors instead of prisms of glass. Special steel from Krupp, which would have been most appropriate, was not available at the time. Therefore, we tried to construct the reflectors from Siemens Martin steel. Unfortunately, we didn't succeed to set up reflectors of size 4x12 cm with a focal distance of at least 1500 m. The reflectors had considerably shorter focal distances at different azimuths such that the interference patterns became hazy and blurred with larger angles of incidence.
Therefore, I had to go back to the glass prisms and to supply the machine above and below with fixed rotation axes. The upper axis was perforated to allow for the entrance of light and, at the same time, the photographic camera was given a flatter shape while bending the light path by means of prisms round the upper axis. Furthermore, the adjusting disposition of the interferometer was improved. Interferences were adjusted, at first, by the prism P_i. Fixing the position of this prism by means of the three screws, however, appeared unsafe. The prism P_i was therefore firmly connected, once for all, to the prismatic arrangement in the centre and another device was chosen to intervene in the light path for the adjustment of the interferences. This device consisted of two wedge shaped glass dishes with a diameter of 4 cm and a wedge angle of 8°. The device was installed into the light path at position C (Fig. 1) so as to allow each wedge independently to be revolved along the axis of the light ray and to be fixed in arbitrary positions. Thus, it was possible to vary the wedge angle continuously between 0° and 6° and to target the thickest part of the wedge for arbitrary azimuths around the incident ray. In this way it was possible to vary the width and orientation of the interferences *ad libitum.* Aligning the incident ray at position C parallel to the centrifugal forces ensured that the rotary motion adjusting width and orientation of the interference stripes ensued in a plane perpendicular to the centrifugal force. The centrifugal force could not, therefore, contribute a torque to the rotary motion. At the wall of the photographic camera a hole of approximately 1 cm in diameter was pierced. Through this hole, light which otherwise would have fallen onto the plate, could leave the device by means of a prism intervening between the tessar and its focal plane. Interference stripes oriented parallel with the rotating plane could be observed, while the machine was rotating, through this hole by means of a telescope focussed onto the focal plane of the tessar.
Looking at the interference stripes through this hole, one could observe their disappearance at 650-700 rpm. This could have happened of course also, if the interference stripes were tilt off their horizontal position because of a displacement of the reflecting face. Pictures taken with the camera rotating together showed, that the disappearance of the interference stripes was, at first, due indeed to a tilting off their horizontal position accompanied by some enlargement of their width. With even larger velocities, at 800-850 rpm, interference stripes became blurred and finally disappeared completely even if the photographic plates were rotating together. In this case, however, their orientation and width remained remarkably unchanged while they were blurring. This led me conclude, that the disappearance of the stripes was not due to a displacement of the reflecting face of the prisms. Because artificial displacement or, what is the same, turning the adjusting wedge at C resulted unequivocally in a change of the interference stripes such that their width became 0 or enlarged to the extent that no stripes could be recognized within the field of view. Pictures of hazy interferences were almost identical to those which I got formerly with the astigmatic steel reflectors at rest. Therefore, I assumed that the final disappearance of the interference stripes was due to an astigmatic deformation of the reflectors caused by centrifugal forces. Because, indeed, the prisms rested on three supporting points only. It should be mentioned that every prism weighing 0.6 kg at rest will be subject to 200 kg by the centrifugal forces at rotation. In order to avoid any deformation of the prisms, I filled the gap between the prisms and the supporting area with

very resistant putty. The surface of the prisms were painted with an extremely thin layer of litharge in glycerol and pressed down to the outer border. This putty complied with my hopes. Having fixed the prisms in the way described above, I was able to get irreproachably sharp interference stripes up to a rotational speed of 2000 rpm. In spite of this success, I refrained from doing final measurements with this device, because the width of the stripes at rotation differed by several percent from their width at rest.

It has been decided, therefore, given all experiences we had gathered, to construct a third machine. Seen from above, with its cover plate removed, the machine is depicted on Fig. 4. The number of reflecting areas has been reduced to a minimum. Only four reflectors have been brought in position and their fixing has been realized with the utmost care. Light entered the machine from above through the hole "O", traversed the rotation axis in axial direction and reached the central prismatic body P_1. It was split, by means of a semi-permeable silver layer, into two coherent bundles, which left P_1 and fell upon the prism P. From there one bundle was reflected to the right side, the other to the left side reaching mirror S_1 and S_4 respectively. The area traversed by the light rays within the interferometer, disregarding the parallelogram between P and P_1, equalled a square with sides measuring 353 mm whose corners were equipped with mirrors reflecting under 45°. Having traversed the square once in opposite directions, both bundles, joining each other at the semi-permeable silver layer, are brought to interference. Interference stripes developed within the focal plane F of the screen T, where a thin slip of glass with engraved measuring marks was located. Interference images including the measuring marks were portrayed by the microplanar objective M (focal distance 8 mm) onto the photographic plate of camera K. Both adjusting wedges are located at position J. The circular glass reflectors are 14 mm thick and measure 5 cm in diameter. In the midst of its back a plug was attached. The front side was plane; the backside was, apart from the plug, a sphere whose radius measured 26 cm. The massive ring RR was made of Siemens-Martin steel. Its interior area had a cross section of 5x6 cm and was likewise of spherical shape with a radius of 26 cm. At corresponding points of the ring RR four boreholes for the four plugs of the reflectors were applied. When the plugs were locked into the boreholes, the spherical backs of the mirrors laid tightly onto the spherical interior area of the ring RR. The mirrors were adjusted, cemented to the ring and, finally, their surface silvered. Due to the fact, that part of the interferometer, i.e. the four mirrors, was fixed to the ring RR, whereas the other part, i.e. the semi-permeable silver layer with the prism P, was fixed to the bottom and cover plate of the machine, it was necessary to take care for an extremely rigid link between the ring and the plates. Both parts were fixed together by use of 18 pairs of cones which could be tightened with screws. The connexion thus achieved was such that, having adjusted the device, interference patterns reappeared immediately without further adjustment after the device had been decomposed and recomposed again. Much pain had to be taken for fixing the socket of the prism P. This part had to sustain a centrifugal force of 500kg at 1500 rpm. After repeated attempts I achieved this goal using very strong grinded cones.

The ready-made arrangement can be seen in Fig. 5. L indicates the Heraeus quartz-Hg-lamp, whose light is focussed onto the diaphragm D (d = 0.5mm) by means of the lens L_1. Behind D a spectral filter is inserted, which was composed of approximately 1 cm thick Didym-glass and thin green glass. This assured that only the green quicksilver line could enter the optical device. Light rays were parallelized by means of the tessar T_0 and projected forward by the pentaprism Pe_1 in perpendicular direction with respect to the shaft. At the crossing between the axis of the bundle and the rotation axis a further pentaprism Pe_2 is fixed, projecting the light bundle along the rotation axis vertically down into the machine. C designates the revolution counter, which is connected by means of a cable to the chronograph. T_1 designates the first, T_2 the second turbine, rotating each in opposite directions and both being fixed to the same axis. A simple switch allowed alternating the rotating direction. V indicates the water-pipe.

This machine was used to make measurements and take pictures during summertime 1925. Such pictures are displayed in original size in Fig. 6. Exposition time was 6 minutes. Pictures 108 and 109 have been taken with the turbine rotating at 1200 rpm in right and left hand direction respectively. Picture 86 was obtained at 1500 rpm, Fig. 7 corresponds to 2000 rpm. The vertical arrows on snapshots 108 and 109 indicate the direction in which interference patterns were shifted. The short horizontal arrows to the left pinpoint to the same interference stripe on both pictures.

Because of the fact, that shifted distance and width of the stripe are proportional to each other under identical circumstances, one should preferably refer to broader stripes, provided the position of those stripes can be determined with the same accuracy as the position of narrower ones. For this goal the pattern of blackening intensities of broader interference stripes was registered by photometric means[1)]. Unfortunately, as Fig. 8 shows, the blackening curves thus obtained were spiked. These spikes were due to tiny particles of dust from the air, which were continuously spun down to the slip containing the measuring marks and were projected along with the interference patterns onto the photographic plate. As a consequence, these pictures didn't even reach the accuracy of pictures with narrower interference patterns. Therefore, I intended to repeat those pictures the following summer using gossamer as measuring marks. Previous experiments convinced me, that this gossamer of 1mm length could sustain the rotation.

[1]) I am indebted to G. Hansen for this registration.

Having applied here and there further improvements, pictures were taken, whose results are listed in the following tables. Pictures 82 through 98 were measured, primarily, by use of a comparator, pictures 117 through 128 were gauged comparing blackening curves according to the method of G. Hansen.

If measurements were done with the comparator each stripe and each measuring mark has been recorded ten times independently. In this way the position X_k of the k-th stripe relative to the measuring mark was obtained. Taking into account the position X_0 of the 0 stripe and the width b of the stripe, equations of the following form can be deduced

$$X_k = X_0 + kb$$

where X_0 and b are unknown quantities. These were determined according to the method of the smallest squares. Results are compiled in both tables.

T corresponds to the revolution time as measured in astral time seconds; b gives the width of the stripe in mm. $\tilde{T}$ and $\tilde{b}$ are mean values of two combined pictures taken from opposite rotating directions. If two successive pictures were not combined, this had to mean that in between both pictures the adjustment of either the reticle or the orientation or the width of the interferences had been corrected. The mean value $\Delta_{\tilde{T}}$ which followed from the measurements belonged to the revolution time $\tilde{T}$, whereas

$$\Delta = \Delta_{\tilde{T}}\,\tilde{T}/0.04$$

belonged to the revolution time T = 0.04 sec astral time. Δ_m is the mean value of the observed Δ. Δ_m therefore belongs to the revolution time T = 0.04 sec astral time, or T = 0.03989 sec mean time. With narrow interference stripes $\Delta - \Delta_m$ amounted to less than 2 percent, whereas with the broad ones it came to surpass 3 percent but once.

The shift Δ listed in the tables has to mean twice the shifting as calculated from equation (1) because two pictures with opposed rotation were always combined. The theoretical value of Δ, as listed in the table, is found from

$$\Delta = 8\omega F/\lambda c$$

The area which the average light ray ran around comprised F = 1178 cm², the angular velocity belonging to T = 0.03989 was $\omega = 157.43\ sec^{-1}$. Substituting $\lambda = 546 \times 10^{-7}$ cm and $c = 3 \times 10^{10}\ cmsec^{-1}$, one finds

$$\Delta = 0.906$$

The observed mean values exceed the value of Δ by 1.2 percent and by a little less than 2 percent respectively. I agree with Mr. v. Laue who uttered in a letter that such a difference between calculated and observed (mean) shifts seems high given the small differences between individual observations.

The investigation has not been finished yet. Besides the green Hg-line, measurements with other wavelengths are planned. In addition, I wished to install a chamber filled with liquid between reflectors S_1 and S_2 and between S_3 and S_4 respectively. The size of the shift should thereby remain unchanged.

I wish to express my sincerest gratitude to the *Notgemeinschaft* and especially to the directory of *Zeisswerke*, among them Sirs Dr. W.Bauersfeld and Prof. Straubel as well as to Sirs Ob.Ing. Meyer, Ing. Büchele and Köppen from the bureau of construction. I am especially indebted to Privy Councillor Mr. M. Wien for his valuable and very kind support as well as to the authorities from the ministry of education of the kingdom of Hungary, who rendered possible to accomplish this work in Jena.

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What is lacking: References, Figures and pictures.
Note: (1)"tessar" was not translated. It seers to be a part (something like a screen) of old photographic cameras, not in use today, may be under another name.
(2) The French text remained untranslated, as it is in the original paper.

Translated by W. Rella, February 2009