Fresnel Dragging Explained
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Abstract
In this paper I show that the effect known as Fresnel Dragging can be fully explained and visualised in terms of Classical Physics when the transmission of light through moving optical media (such as water) is modelled as a process of continual absorption and emission rather than a continuous process determined by the medium’s refractive index. Previously the result of the famous Fizeau experiment of 1860 has been explained using Special Relativity, however, this paper shows that this analysis is unnecessary and Classical Physics can explain the effect.

Indexing terms/Keywords

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Theoretical Physics, Classical Physics, Mathematics.

SUBJECT CLASSIFICATION
Theoretical Physics, Mathematics.

TYPE (METHOD/APPROACH)
Theoretical Physics Modelling, Mathematical Proof.

INTRODUCTION
Fresnel Dragging is the change in the apparent speed of light that occurs when light is transmitted through moving optical media, such as water. The effect was measured in the famous experiment carried out by M. H Fizeau in 1860 [1]. In this experiment an interferometer was used to compare the travel times of two beams of light, with the same origin, travelling through moving water – either in the direction or in the opposite direction to the water flow. When the two beams of light were recombined, there was a shift in the interference fringes in the interferometer due to a phase difference in the beams, indicating a difference in the travel times for the two beams of light.

According to Fizeau’s analysis the shift in the interference fringes of the light in the interferometer is approximated by the following equation:

$$\delta = 4L \frac{c}{\lambda v} (n^2 - 1)$$

(1)

The amount it is delayed is not by the speed of the water \( (v) \), but by a fraction of its speed \( (v') \), determined by the Fresnel dragging coefficient:

$$v' = v \left(1 - \frac{1}{n^2}\right)$$

(2)

However, rather than an approximate value, the exact amount of the interference fringe shift can be calculated as follows, by considering the following points:

1. Different optical path lengths due to the moving water.
2. Two light waves of equal wavelength entering the tube (containing flowing water) in phase, but travelling in opposite directions will arrive at the end of the tube out of phase.

$$c_n = \frac{c}{n}$$

(3)
CLASSICAL EXPLANATION FOR FRENSNEL DRAGGING

The Fresnel Dragging effect has in the past been explained by Special Relativity, however the effect can be explained fully by Classical Physics. The key to understanding how the effect occurs lies in the understanding that as the light propagates through moving water it is being continually absorbed and re-emitted by each water molecule it encounters during its journey.

Whilst the light quanta are absorbed by the water molecules, the light is slowed by refractive index factor $n$ and carried by the water molecules at their full velocity, but when travelling between water molecules it travels at the normal, full speed of light (through the space between water molecules that is considered to be stationary with respect to the water).

The assumption that the light wave is slowed evenly and travels at a constant $c_n$ through stationary water is wrong. The reality is that the transmission is a stop/start process, with the light slowing as it interacts with each water molecule, but travelling at full light speed between molecules. As a result of this, the $c_n$ terms used in the equations that describe the travel times in the Fizeau experiment need to be modified to account for this difference.

Armed with this understanding, we can now analyse the experiment successfully:

When the water is flowing through the tubes in the experiment, the wave of disturbance due to the light wave propagating in the water is carried along with the water at the water’s full velocity, as one would expect in a classical sense, causing the rate of passage of light to be increased or decreased, depending if the light is travelling in the same direction as the water flow, or against it. However, as the water molecules do not take up the whole volume of space, there exists space between them where the light travels at the normal speed of light with respect to the stationary reference frame. The distance that the light travels before it encounters another water molecule is a function of the speed at which light travels through space and the speed at which the water is travelling.

In stationary water the time that light travels through space between water molecules before encountering another water molecule will be the same in either direction down the tube. However, as the water is moving in the experiment, the distance the light must travel through space until it encounters another water molecule will either increase or decrease depending if the light is travelling in the same direction as the water or against the direction of the water flow.

By taking into account these two effects that are occurring in the experiment simultaneously and in opposite directions, the total delay on the travel of the light beam can be calculated.
If we consider the upstream direction as a case in point:

![Diagram](image1)

**Figure 1:** If the light between the molecules moved at \( c_n \), then \( v \Delta t \) would be the distance the water had moved during its travel between molecules before it meets the light wave coming from the opposite direction.

![Diagram](image2)

**Figure 2:** But the light between the molecules moves at \( c \), so the water has moved \( \frac{v}{n} \Delta t \) less during its travel between molecules before meeting with the light wave.

So, as the water is moving at speed \( v \) through the apparatus, during the time that the light takes to travel through the empty space region (at speed \( c \) rather than at speed \( c_n \)), it will have travelled \( n \) times less distance: so \( \frac{v}{n} \) less distance travelled by the water in the same time period.

So this means that during the light’s passage through the apparatus there is a distance of \( \frac{v}{n} \) less in which it will encounter water molecules and be slowed by factor \( n \) as a result of the encounter.

The two light path travel times in the Fizeau experiment are:

\[
t_1 = \frac{2L}{c/n - v} \quad (8) \quad t_2 = \frac{2L}{c/n + v} \quad (9)
\]

In calculating the \( c_n \) terms in these two equations to account for the difference in travel times of the light between water molecules in the upstream/downstream direction, the situation can be thought of as the case where the water is stationary, but the speed of light in a vacuum is different in the up/down directions. Thus if treated mathematically as a differential in the speed of light in the up/down stream directions the light travels in the upstream direction at a speed that is higher than \( c \) (the normal speed of light in empty space) and at a speed that is slower than \( c \) in the downstream direction.

In the new analysis, we need to use the following new definitions:

\[
c_{\text{up}} = c + \frac{v}{n} \quad (10) \quad c_{\text{down}} = c - \frac{v}{n} \quad (11)
\]

The reason for these definitions is that if the light travels unimpeded at speed \( c \) when between water molecules, rather than at \( c_n \) through the whole distance, then the distance travelled by the next water molecule that is about to receive the propagating signal will be different by the amount \( \frac{v}{n} \) per unit of time (added on or subtracted from \( c \)).
Therefore I have calculated the distance per unit time that the light wave has effectively travelled \((c + \frac{v}{n})\) upstream or \(c - \frac{v}{n}\) downstream) and then substitute these new values into equations (8) and (9) where the speed of light \(c\) appears:

So equations (8) and (9) become:

\[
t_1 = \frac{2L}{c + \frac{v}{n}} - \frac{2L}{c - \frac{v}{n}} = \frac{2L}{c - v(1 - \frac{1}{n^2})}
\] (12)

\[
t_2 = \frac{2L}{c - \frac{v}{n}} = \frac{2L}{c + v(1 - \frac{1}{n^2})}
\] (13)

Then substituting equation (2) into (12 and (13) gives:

\[
t_1 = \frac{2L}{c - v'}
\] (14)

\[
t_2 = \frac{2L}{c + v'}
\] (15)

Then to get the overall result, we combine the two times:

\[
t_1 - t_2 = \frac{2L}{c - v'} - \frac{2L}{c + v'}
\]

\[
t_1 - t_2 = \frac{2L \left( \frac{c + v'}{n} - \frac{c - v'}{n} \right)}{\frac{c^2}{n^2} - v'^2}
\]

\[
t_1 - t_2 = \frac{4Lv'}{\frac{c^2}{n^2} - v'^2}
\] (16)
CONCLUSION

So using (16) the total fringe shift is:

$$\delta = \frac{c \Delta t}{\lambda_0} = \frac{4cLv'}{\lambda_0 \left(\frac{c^2}{n^2} - v'^2\right)}$$

(17)

This is the same as equation (7) from my analysis at the start of this paper.

Thus the effect of Fresnel Dragging can be completely explained by Classical Physics once the process is modelled as a stop/start process of absorption and emission of light by the water molecules, with the light travelling between molecules at the speed of light in a vacuum.

Note: This result assumes monochromatic light is used in the experiment, as the effect of dispersion due to spreading of different component frequencies is not included here. A small correction needs to be made if not using monochromatic light.

REFERENCES


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