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Fundamental Principles of Fibre Fineness Measurement

Part 7

Optical Diffraction



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OPTICAL DIFFRACTION

Principle

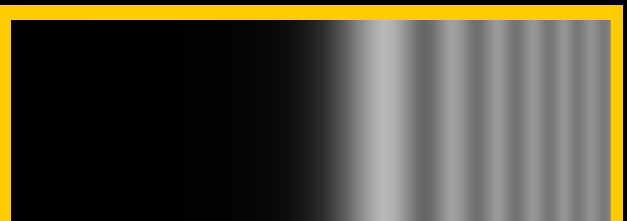
Diffraction is a change in the direction, or bending, of a wave into a region where it would normally be obscured (the geometric shadow). All wave phenomena, including electron beams, which can exhibit wave-like behaviour, are subject to diffraction. It is easily observed in water waves, which can bend around an obstruction in the water.

The effect is especially important in the case of visible light, as it affects the design and performance of optical instruments. There are two major cases in which light diffraction is observed. In the first, light that passes through a small aperture does not form a sharp image of the aperture on a screen; the image is diffuse, and a series of bright and dark rings, or fringes, outline the image and fall within the predicted geometric shadow of the aperture. This effect is directly observed only if the size of the aperture is no wider than a few wavelengths of light, or less than a millimetre. The second case occurs when light is bent around the edge of a smooth object (such as a wool fibre). In the region of the geometric shadow there is a series of fine bright and dark fringes instead of the predicted sharp shadow edge.

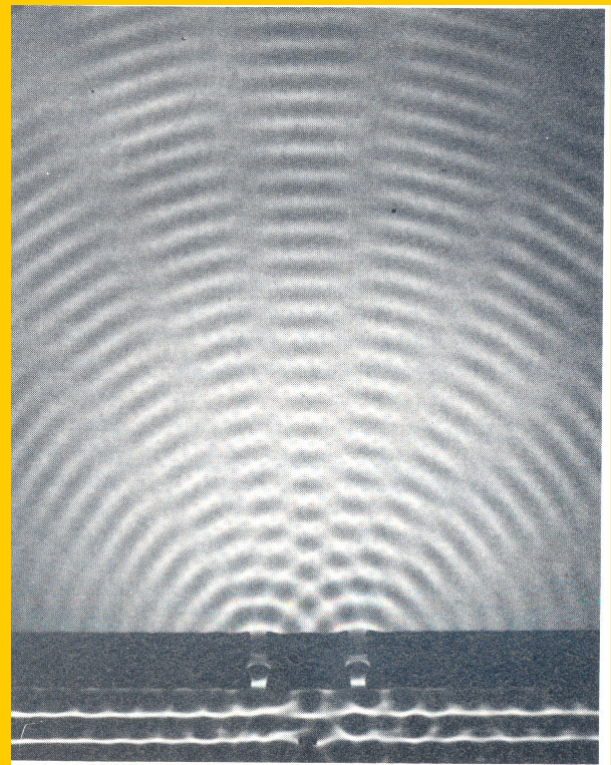
Diffraction is considered a wave phenomenon, and its explanation by Augustan Fresnel in 1814 played an important part in establishing the wave theory of light. The basis for the wave theory is traced to Christian Huygens (1629-1695), who proposed that each point on a wavefront may be regarded as a new source of waves. Thus, each point on a wavefront is the resultant of the many contributions of secondary waves from the previous wavefront. Toward the centre of the beam these secondary waves combine in such a way as to transmit the light in straight lines. Diffraction results from the obstruction of a portion of the light, which removes some secondary waves. These ordinarily would cancel other waves that travel into the geometric shadow; thus some light is observed in this region.

For historical reasons diffraction phenomena are classified into two types: Fraunhofer and Fresnel diffraction. Fraunhofer diffraction treats cases where the source of light and the screen on which the pattern is observed are effectively at infinite distances from the intervening aperture. Thus, beams of light are parallel, or the wavefront is plane, and the mathematical treatment of this type of diffraction is simple and elegant. Fresnel diffraction treats cases in which the source and the screen are at finite distances and therefore the light is divergent. This type of diffraction is easier to observe, but its complete mathematical explanation is considerably more complex.

The theoretical application of diffraction to measure the mean diameter and the standard deviation in diameter of fibres was discussed by Onions (1959). Onions showed that when monochromatic light is



Diffraction pattern produced by a straight edge.



Diffraction pattern produced by water waves passing through two parallel slits.



incident on a slit, in a direction perpendicular to the plane of the slit, the expression for the intensity of the light at an angle θ may be written:

$$I = A_o d_w^2 \cdot \left(\frac{\sin^2 \beta}{\beta^2} \right) \quad 1$$

where

$$\begin{aligned} A_o &= \text{a constant;} \\ d_w &= \text{the width of the slit;} \\ \beta &= \frac{\pi d_w \sin \theta}{\lambda}; \\ \theta &= \text{angle of diffraction; and} \\ \lambda &= \text{wavelength of the light.} \end{aligned}$$

In a group of fibres, all approximately parallel to the slit, different fibre elements will generally vary in diameter and will simultaneously intercept different proportions of the light beam. Onions assumed that the arrangement of fibres approximated a group of equivalent slits. From this he showed that for a case where the fibre diameter is normally distributed then the radial distribution in intensity is given by:

$$I_{T,\theta} = A_o \int_0^\infty D^2 \cdot \left(\frac{\sin \beta}{\beta} \right)^2 \cdot \frac{N}{s\sqrt{2\pi}} \cdot \exp\left[-\frac{(D-\bar{D})^2}{2s^2}\right] dD \quad 2$$

where

$$\begin{aligned} I_{T,\theta} &= \text{the intensity of the light at an angle } \theta; \\ D &= \text{the fibre diameter;} \\ \bar{D} &= \text{mean fibre diameter;} \\ s &= \text{standard deviation in diameter; and} \\ N &= \text{the number of fibres in the specimen.} \end{aligned}$$

From this it is not difficult to show that:

$$I_{T,\theta} = \frac{B_o}{\phi^2} \left[1 - \cos \phi \cdot \exp\left(-\frac{(D-\bar{D})^2}{2s^2} \cdot \phi^2\right) \right] \quad 3$$

where

$$\begin{aligned} \phi &= \frac{2\pi\bar{D} \sin \theta}{\lambda}; \text{ and} \\ B_o &= 2NA_o \bar{D}^2 \end{aligned}$$

Based on this theoretical model, Onions proposed a design of an instrument that could measure Fibre Diameter and also the Standard Deviation in Diameter.

Development

Young (1824) was the first to adapt the phenomenon of light diffraction to the measurement of fibre diameter. Ewles (1928) made an instrument based on the principle, which consisted of a portable tube, but gave no experimental information about the comparative data in measurements obtained with this instrument

Duerden (1921) reported experiments with a laboratory diffraction apparatus. He made a large number of measurements, using microscopic and diffraction methods, and found a very close agreement.

Burns (1930) reported a few measurements with the Ewles instrument as compared with the micrometer calliper, and found that the micrometer measurements were on average about 5 micrometres finer than the readings taken by the Ewles instrument.



McNicholas and Curtis (1928) reviewed the history of diffraction instruments and described an improved device called an eriometer. They made an extensive study of the accuracy and adaptability of the eriometer in averaging a wide range of diameters, as distributed in a sample of fibres. They found the average fineness obtained with their eriometer agreed closely with the microscope and concluded that "... *the diffraction method offers considerable opportunity for the further development of instruments to include other features that are desirable in the study of wool and other textile fibres.*"

Mathews (1932) reported that long straight fibres are the easiest to measure by the diffraction technique. "*One must be careful to prepare the wool sample so that the fibres are parallel, doing away with the fuzziness of the bands that are so prevalent when the fibres are crossed over one another.*"

Von Hertzog (1932) gave a description of a light interference method for the estimation of fibre thickness, firstly by means of polarised light, and secondly by means of a special polarisation apparatus.

The reporting of studies of light diffraction techniques applied to wool metrology suddenly disappeared from the literature until Onions wrote his paper describing the physics of the system in 1959. Onions' theory was discussed by Whan and Paynter (1967). Boshoff and Kruger (1971) described the Mikronmeter, an instrument based on the original design by Ewles (1928) and Onions (1959). The instrument measured the circular diffraction pattern produced by a sample of randomly oriented fibres. The authors claimed that a well trained operator could measure fibre diameter very accurately while randomly chosen operators could determine fibre diameter with a confidence interval of ± 0.8 micrometres. However occasionally, some operators could not use the instrument correctly.

Lynch and Thomas (1971) examined the diffraction patterns produced by wool and other fibres by single fibres in a helium-neon laser beam and suggested that a possible application was the determination of fibre diameter.

Edmonds (1988) reported results obtained using a diffraction instrument where the diffraction patterns were recorded as photographic images and later analysed. In this device the samples were randomly oriented, but the diffraction pattern was obtained by rotating the sample in front of the slit in the instrument. Edmonds found a correlation of 0.95 with the Projection Microscope method but only a 0.5 correlation for standard deviation.

Fouda, El-Dessouki and El-Farhaty (1988) reported a study using a laser as a source of coherent light to examine the diffraction patterns produced by a range of synthetic fibres. They examined three techniques, and found the forward light scattering technique the most satisfactory.

Technical Issues

The Mikronmeter was commercialised shortly after Boshoff and Kruger's paper was published. The instrument arrived on the market almost at the same time as work was commencing in Australia to extend the testing of greasy wool to farm lots prior to auction. The target market for the instrument was wool growers, wool brokers, wool buyers and wool processors. The instrument was then available for A\$135.

David & O'Connell (1972) reported the results of a trial to evaluate the precision of the Mikronmeter. They found the same difficulty with some individual operators that were reported by Boshoff and Kruger. They concluded that contrary to the data reported by these authors a precision of only ± 2 micrometres could be achieved and only then if 5 sub-samples were measured.

The experience with the Mikronmeter appears to have sounded the death knell for this technology, with very little interest since 1972, except for the two studies reported above. However active development of the technology has continued in other industries and diffraction techniques are currently being applied to estimate diameters of optical fibres. The abandonment of the technology by the wool industry is possibly a good example of how an immature technology can lose favour very quickly if it is released too early into the market.



Commercial Issues

Optical diffraction has never found a successful commercial application in the wool industry. However, with the increasing interest in Australia by wool growers in testing their flocks prior to shearing, and using the data to assist in classing, the technology is currently being revisited.

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Huygens lived from 1629 to 1695. Following the death of Descartes, Huygens was the most celebrated mathematician in Europe. He developed the wave theory of light, from focusing on the diffraction and refraction properties he could observe. "Huygens's wavelets" were the formal basis for explaining these phenomena

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