Lasers and CCDs for flash measurement of small diameters

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Abstract

A pulsed diode laser casting a diffraction pattern shadow on a CCD is investigated as a non-contact micrometer. Data collected with a prototype instrument are compared with calculated diffraction patterns. Computational needs and possible techniques for diameter extraction are discussed.

Background

Laser micrometers have been available for several years. In the commercial instruments a rotating mirror at the focus of a transmitting lens scans a CW laser beam perpendicular to its propagation direction. A single detector is located at the focus of a receiving lens. The target object is placed between the transmitter and the receiver. Measurement of the occlusion time determines the diameter. The method is obviously unsuitable for targets in transverse motion at any substantial fraction of the scan velocity.

This paper discusses research towards an alternative laser micrometer technique using a pulsed laser and spatial occlusion measurement by a CCD linear array. Instruments using fast pulsing and spatial occlusion potentially overcome the velocity limitation of temporal occlusion instruments. They might also be smaller and less expensive. Their hardware is simple, and they have no moving parts and few adjustments. However, high demands are placed on algorithms for signal deconvolution; indeed, it is at this writing uncertain that a method for obtaining competitive precision at an acceptable computing burden can be devised.

Prototype instrument

The prototype instrument uses a pulsed diode laser, a spherical transmitting lens, a cylindrical receiving lens, a CCD detector, and a microcomputer controller. The target, e.g., wire, is inserted between the transmitting and receiving lenses, casting a shadow on the CCD. Some essential details are:

Laser. The pulsed laser diode is rated at near 20 watts (peak) with a pulse duration under 200 nsec and a repetition rate of up to about 2 kHz. The optical wavelength is approximately 895 nm. The laser is operated at just enough power to obtain uniform output intensity across the 2 μm by 200 μm active cross section.

Transmitting lens. The spherical transmitting lens is an inexpensive 5X, 0.1 NA microscope objective lens used as a collimator for the inherently diverging diode laser beam.

Receiving lens. The cylindrical receiving lens, 1 cm focal length, focuses a planar wavefront into a line coincident with the CCD array. This geometry is appropriate for measuring the diameter of essentially cylindrical targets more or less perpendicular to the plane defined by the lines of the laser beam and the CCD array. In an instrument for more general applications, this lens would probably not be used, and higher laser power might be used in compensation.

CCD. The CCD is a 256-cell chip with 5 μm active cell widths on 13 μm centers. It is mounted on a manufacturer’s evaluation kit board and clocked by signals from the microcomputer instead of the on-board oscillator. A gain stage with an offset adjustment was added to the board’s analog output stage to more effectively interface it to the ADC.

ADC. The ADC is a 6-bit flash converter on a manufacturer's evaluation kit board under control of the microcomputer.

Microcomputer. The single board microcomputer uses a Z8 chip with a Tiny BASIC interpreter in internal ROM, the control and data acquisition program in external ROM, and external RAM for data memory. The BASIC program is a few lines that set the data collection parameters and loop through a cycle of calls to machine language procedures that fire the laser, clock the CCD, clock the ADC, read the ADC into RAM, and on receipt of a request on the serial input line, move blocks of data onto the serial output line, e.g., for transfer to a data analysis computer.

Diffraction shadow

The observed shadow is in fact a highly structured diffraction pattern. This seemingly undesirable complication could of course be practically eliminated by focusing an image of the back-lighted (or for that matter, front-lighted) target on the CCD. Were this done with the lens closer to the CCD than to the target, the demagnified image of a small diameter object would occupy only a few pixels, perhaps only one, and if one, then because of the 5/13 sensitive area ratio, then perhaps actually zero. On the other hand, were it done with the lens closer to the target than to the CCD, i.e., with magnification, the necessary insensitivity to precise axial location of the target would be lost. Furthermore, imaging optics are a potentially serious liability in hostile industrial operating environments. Thus several considerations, foremost among them the desirability of an instrument not too sensitive to the target's axial position, point to making it work by developing algorithms able to extract the diameter from the diffraction pattern in real time.

The diffraction pattern is not necessarily disadvantageous in comparison with a geometrical shadow: in principle the wiggles capture a diameter measurement with interferometric precision, and because they spread this information over many pixels, problems of finite pixel size might potentially be overcome. However, not all of the signal power is tightly coupled to the diameter. The diffraction pattern can be thought of as having three components. The dominant two components are the diffraction patterns of two slightly offset knife edges, each contributing wiggles spaced approximately as the differences between consecutive values of $(2\ n\ \lambda\ \rho)^{1/2}$, where n is an integer, λ the wavelength of the light, and ρ is the distance from the target to the CCD. The third and much weaker component is the interference between them, with wiggles spaced approximately as $\lambda\rho/\delta$ where δ is the target diameter. Thus in this intuitive approximation only the weakest feature of the pattern is sensitive to the sought parameter. Unless the measurements are made with excellent signal-to-noise, and with high resolution digitization, it might prove difficult to extract the weak high-precision information buried in the strong low-precision information.

Data and theory

Figures 1 through 4 compare exemplary data collected by the prototype apparatus with wires of 404 µm (26 awg), 320 µm (28 awg), 203 µm (32 awg), and 102 µm (38 awg) with exemplary diffraction patterns calculated for the apparatus geometry for wires of 400, 320, 200, and 100 µm. The target-to-CCD distance is about 16.7 cm. This distance, dictated by an anticipated application, is substantially more than would be desirable in an instrument designed for routine applications.

The calculation method is a brute force Huygens' Principle approach (incorporating the Kirchoff[1] obliquity factor modification) with integration across the wavefront, and across the CCD's sensitive areas, each at 1 µm intervals. Artifacts that arise when the beam is abruptly cut off are circumvented by arbitrarily defining the wavefront as a parabolically attenuated gaussian whose amplitude goes through zero at the lens radius, where the integration is terminated.

The resulting calculated wavefront at the CCD plane has macroscopically more droop than does the experimental wavefront, but the experimental wavefront is rich in spatial noise. The data are smoothed by a nine point linearly-weighted sliding average, and normalized by dividing the dark-current corrected signal intensity by the dark-current corrected unobstructed wavefront intensity. The calculation is similarly normalized. This normalization, while arbitrary, substantially reduces (but clearly does not entirely eliminate) artifacts attributable to the non-uniform wavefront.

Contrast is somewhat worse in the data than in the calculation, but this is obviously to be expected. The major features of the data and the calculation are clearly in good agreement. Minor features are lost in the data due in part to the 6-bit ADC resolution, and in part to the failure to completely normalize out the wavefront structure. The former problem may be remedied by using a higher resolution ADC, and the latter by spatial filtering of the laser.

Diameter extraction

Computational methods for extracting diameters from the data are under study, and will be discussed at the conference. Methods under consideration include spatial frequency spectral analysis by FFT, moment analysis about the nominal axis of symmetry, and analysis of the spacing between peaks, valleys, and zero crossings, i.e., locations where the signal and the unobstructed wavefront are of equal intensity.

The challenge is to develop a normalization method that produces translational invariance, i.e., a transformation that makes the data insensitive to both target offset from the center of the CCD array, and to CCD offset from the center of the laser beam axis.

Conclusions

Shadows cast by wires obstructing a pulsed diode laser illuminating a CCD exhibit a wire diameter dependent diffraction structure in excellent agreement with a Huygens' Principle calculation. Efficient extraction of the diameter from the data is inhibited by the dependence of the patterns on wavefront inhomogeneity.

Acknowledgements

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Reference

1. Francis A. Jenkins and Harvey E. White, Fundamentals of Optics, McGraw-Hill 1957, p.378.

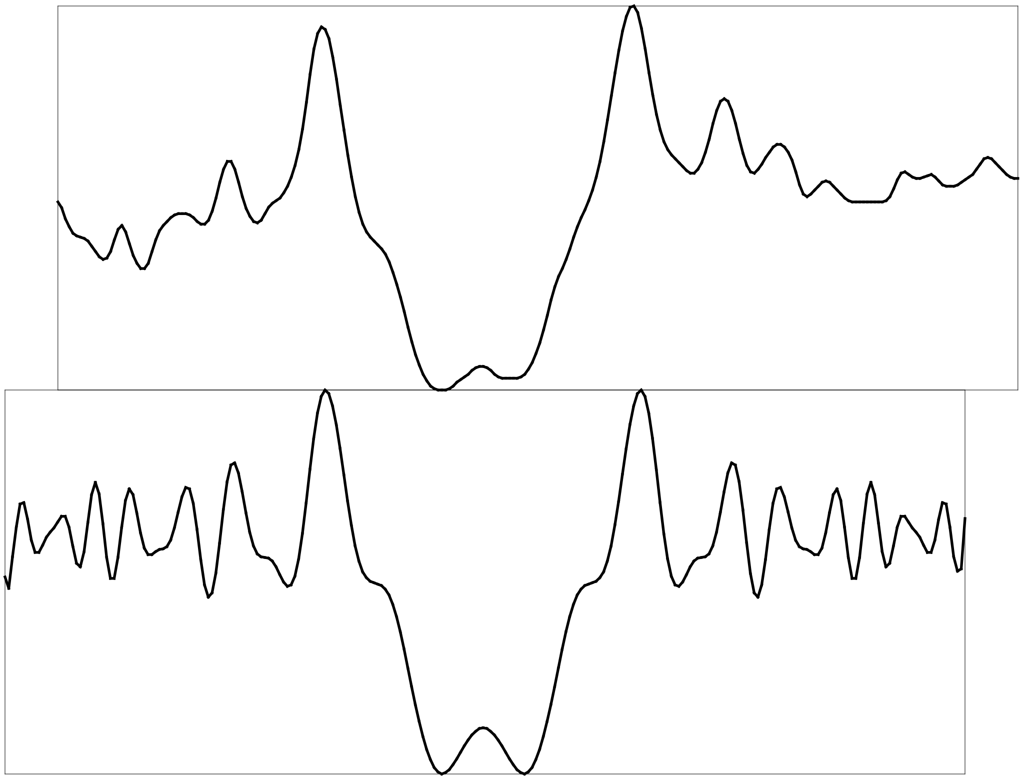

Figure 1. Normalized diffraction pattern of 404 µm (26 awg) wire, measured (top), and calculation for a 400 µm wire (bottom)

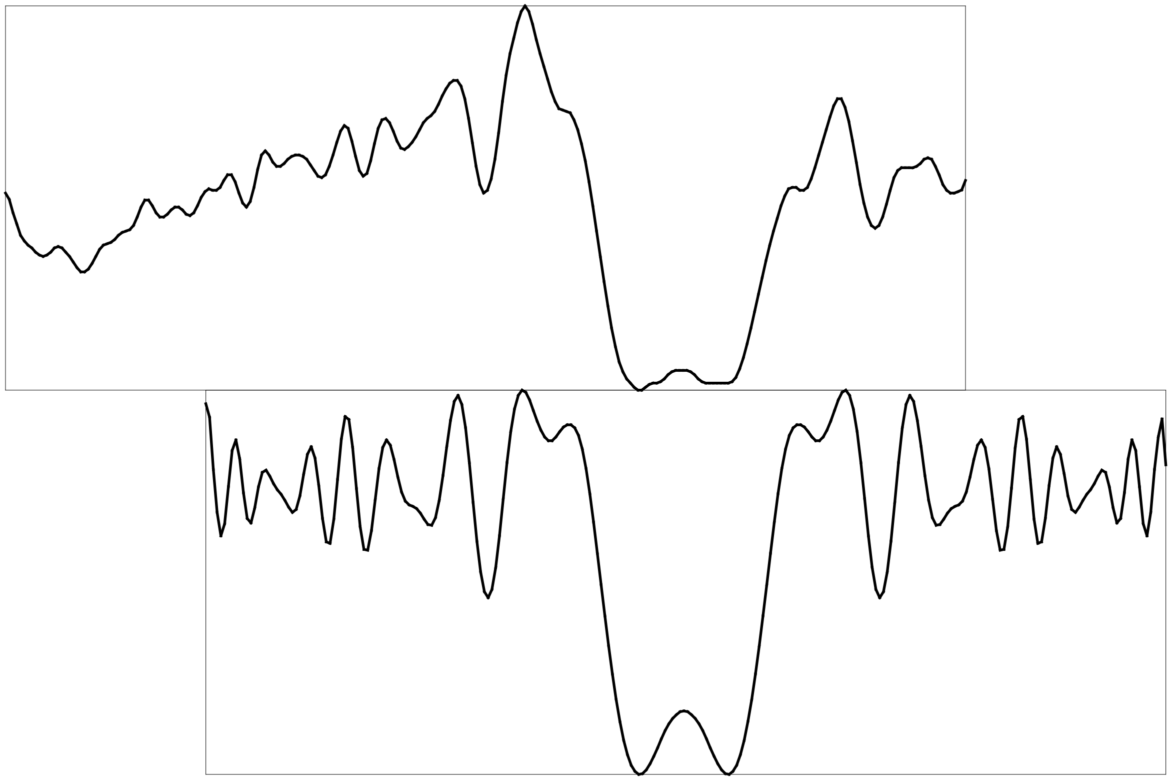

Figure 2. Normalized diffraction pattern of 320 µm (28 awg) wire, measured (top), and calculation for a 320 µm wire (bottom)

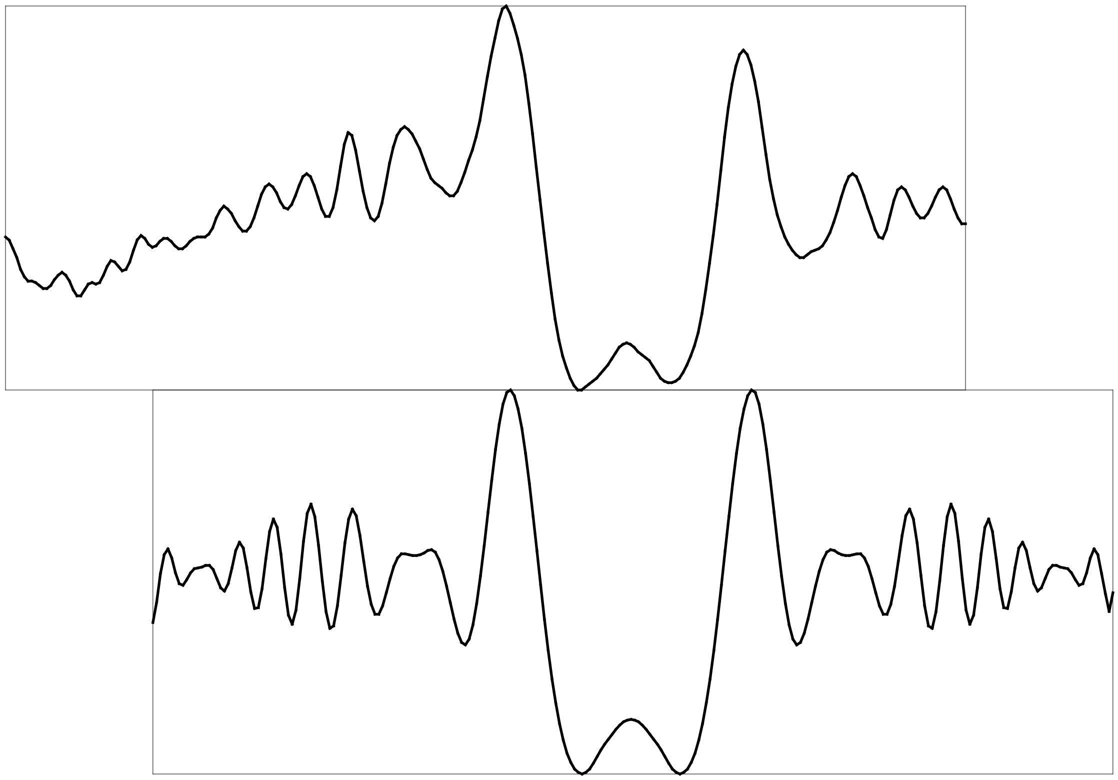

Figure 3. Normalized diffraction pattern of 203 μm (32 awg) wire, measured (top), and calculation for a 200 μm wire (bottom)

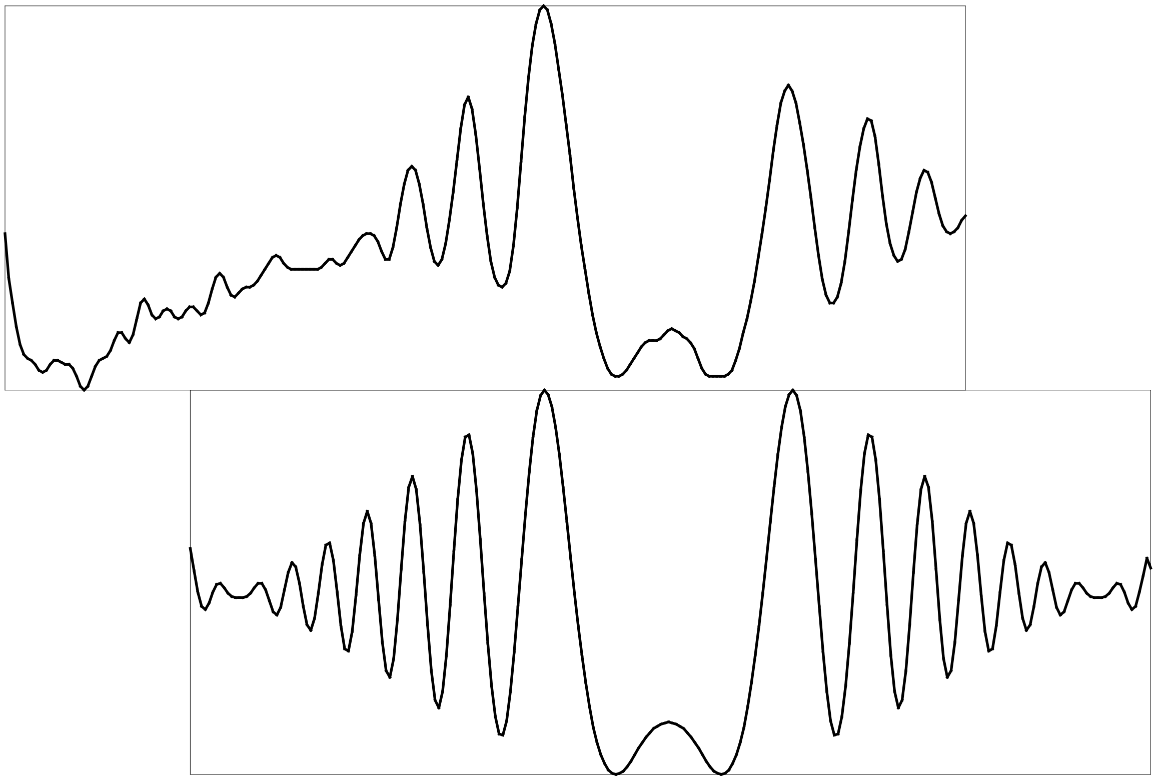

Figure 4. Normalized diffraction pattern of 102 μm (38 awg) wire, measured (top), and calculation for a 100 μm wire (bottom)