Combustion Diagnostics by Electronic Interferometry Using a CCD Image Sensor

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ABSTRACT

Computer-based new interferometric methods for the particle characterization and the refractive index distribution measurements relating to the combustion field are proposed. The first is electronic speckle pattern interferometry (ESPI) using some sets of speckle pattern data, by which the refractive index distribution depending on the temperature, the pressure and the component concentration can be measured in real-time. The second is the phase visualization of diffraction patterns, by which the size and position parameters of particles can be separated.

An electronic optical data processing system whose main componets are a 2-D CCD image sensor, a frame memory and a 16-bit microcomputer was build. Using this system, the ESPI was carried out on a town gas flame and clear fringes were successfully generated. The phase of diffraction pattern of particles was visualized and their size and position were calculated with a great accuracy.

INTRODUCTION

Measurering methods by which results can be obtained as two or three dimensional pictures are very important in combustion analysis. Holographic interferometry is useful for measurements of refractive index distribution in the combustion field relating to the temperature, pressure and component concentration, and in-line holography is applied to characterization of particles in spray, etc. These methods have used photographic materials as recording media and require the time-consuming and troublesome processes. But combustion phenomena are very complicated and enormous data are necessary for analysis. Therefore, measurements are desired to be automatic and real-time in data acquisition and processing.

According to this requirement we have developed an electronic optical data processing system mainly composed of a 2-D CCD image sensor, a frame memory and a 16 bit micro-computer for the electronic speckle pattern interferometry and the interferometric phase visualization of diffraction patterns. The former is a similar method to holographic interferometry but requires not so high resolution recording media as in holography, and can be applied to the measure-

ments of refractive index distribution. On the other hand the latter is applied to the measurements of particle size, position and velocity.

Computer-based digital processing of optical data makes it possible to realize processings such as subtraction, multiplication, division and complicated calculations of the light intensity, which cannot be realized by conventional optical holography, speckle pattern interferometry, optical filtering etc. using physical phenomena. These features will develop various new measurement methods in combustion diagnostics.

DISCRIPTION OF THE SYSTEM FOR ELECTRONIC INTERFEROMETRY

The developed system for electronic interferometry is shown schematically in Fig. 1. The output light from an interferometer such as the Mach-Zehnder, the Michelson or the speckle pattern interferometer is introduced on to the face of an image sensor through a lens or without a lens. A CCD (solid-state charge couple device) image sensor with 384x490 elements is used. The photoelements are positioned on 23 μm horizontal centers and 13.5 μm vertical centers. It has an optical area of 8.83 mm by 6.62 mm.

The output video signal is converted to the 8-bit digital signal for digital storage and computer based processing. One frame of picture has 188 kByte information. In the method developed in this study two interference patterns are necessary at least. Then, the storage capacity of the memory must be more than 376 kByte. A 16-bit microcomputer has a sufficient address space to access the memory with such capacity directly. However, the frequency of the driving clock is 7.16 MHz, which is too high for the video signal to be written into and read from the memory by the CPU. Then, we designed a system in which the video memory can be connected with or isolated from the CPU, the camera, and the display monitor, respectively. By this constitution the processing time can be highly shortened even with a microcomputer at a low cost. The video signal is directly written in the RAM by generating the address signal with a counter driven by the clock of the image sensor, when the RAM is isolated from the CPU by closing the buffer between the CPU and the camera.

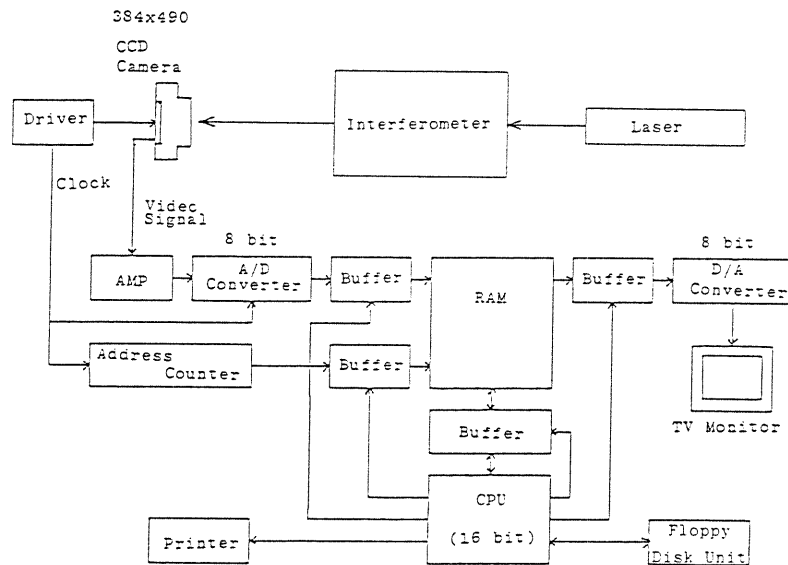After recording, the buffer between the CPU and the RAM is opened and the CPU processes the

Fig. 1 Schematic diagram of the electronic interferometry system.

data in the RAM directly. After the camera's clock the processed data are converted to analog video signal and displayed on a TV monitor, the buffer between the CPU and the RAM being closed. As a auxiliary memory, a floppy disk unit is used.

MEASUREMENTS OF REFRACTIVE INDEX DISTRIBUTION BY ELECTRONIC SPECKLE PATTERN INTERFEROMETRY

Speckle pattern interferometry is a technique visualizing the phase change produced by the deformation of solid objects, the refractive index change in fluids, etc. The laser light scattered by the rough surface generates the speckle pattern in the image field or in the diffraction field. In speckle pattern interferometry the phase information of the speckled light from the object is stored in a recording medium in the form of the interference pattern produced by superposing the reference light on the object light. After the phase of the object light is changed by the deformation of solid objects or the change of the refractive index of transparent fluids, the interference pattern of the speckled light from the object and the refence light is stored again. The phase change between two states of the object light is acquired as fringes of equi-phase difference contours produced by processing the two patterns. In the methods using photographic materials as storage media, the developing process is very time-consuming, and the fringes produced by physical means such as absorption, diffraction, etc. have low visibility.

Electronic speckle pattern interferometry can remove these drawbacks since the data of speckle interference pattern are acquired by a electonic camera as a video signal and processed electronically. Especially, digital processings using computers have a wide feasibility, since they are free from the physical phenomena. Digital video memories also help to generate clear fringes for two sets of read video signal have no shear each other, while in analog memo-

ries such as a magnetic disk they may have some shear decreasing the correlation between two patterns.

Data processings in ESPI

We developed some methods of data processing based on digital computing in ESPI [1,2]. Here the methods using four frame data are described. Consider an optical configuration shown in Fig.2. Let the complex amplitudes of the object light before and after a change of phase be $U_1\exp(i\varphi_1)$ and $U_1\exp(i\varphi_1+i2k\delta)$, respectively, and that of the reference light be $U_2\exp(i\varphi_2)$ on the face of the image sensor, where φ_1 and φ_2 denote the random phases produced by the diffusers inserted in the path of the object illumination light and the reference light, 2δ is the change of the optical path length of the object light, and $k=2\pi/\lambda$(wavelength). The intensities of the object light and the reference light, and the two interference patterns before and after phase-changing are represented by

$$I_o = |U_1|^2 \tag{1}$$

$$I_r = |U_2|^2 \tag{2}$$

$$I_1 = I_o + I_r + 2\sqrt{I_oI_r}\,\cos(\varphi_1-\varphi_2) \tag{3}$$

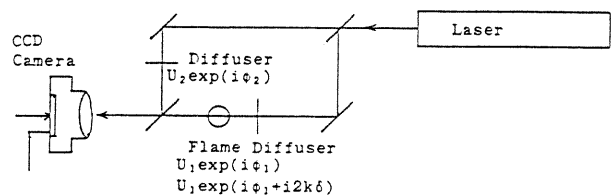$$I_2 = I_o + I_r + 2\sqrt{I_oI_r}\,\cos(\varphi_1-\varphi_2+2k\delta) \tag{4}$$

respectively.

Fig. 2 Setup for electronic speckle pattern interferometry.

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SUBTRACTION MODE	$I_1 - I_2 = 4\sqrt{I_o I_r}\ \sin(\varphi_1 - \varphi_2 + k\delta)\ \sin(k\delta)$	(5)
ADDITION MODE	$I_1 + I_2 - 2(I_o + I_r) = 4\sqrt{I_o I_r}\ \cos(\varphi_1 - \varphi_2 + k\delta)$	(6)
NORMALIZING SUBTRACTION MODE	$(I_1 - I_2)/4\sqrt{I_o I_r} = \sin(\varphi_1 - \varphi_2 + k\delta)\ \sin(k\delta)$	(7)
NORMALIZING ADDITION MODE	$I_1 + I_2 - 2(I_o + I_r)\ /4\sqrt{I_o I_r} = \cos(\varphi_1 - \varphi_2 + k\delta)\ \cos(k\delta)$	(8)

Table 1 Data processing in ESPI
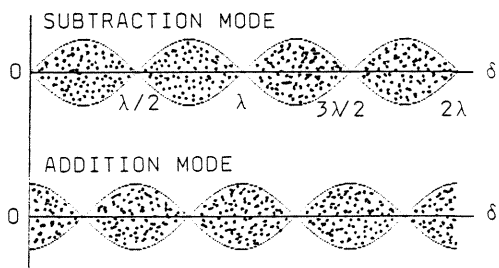
Fig. 3 Schematic illustration of the fringe formation in ESPI.

The calculation methods to extract information of phase change of the object light are summarized in Table 1. In which mode, the results are distributed stochastically in two envelopes with different signs which are the sinusoidal functions of the optical path length to be measured as shown in Fig. 3. When the results are displayed on the TV monitor, it is necessary to convert negative results to positive values by squering or taking their absolute, since the negative brightness cannot exist.

The subtraction mode is the simplest and gives clear fringes easily for the sake of the elimination of the noise common to both speckle interference patterns.
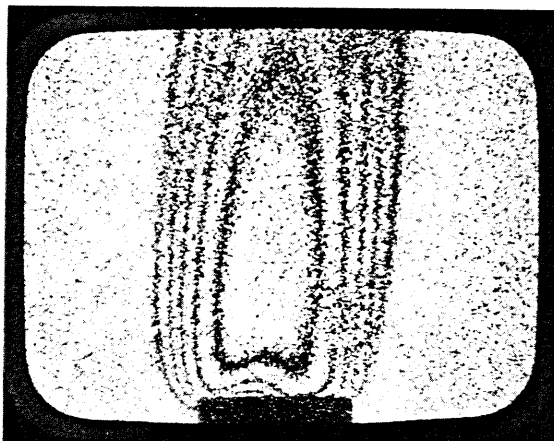
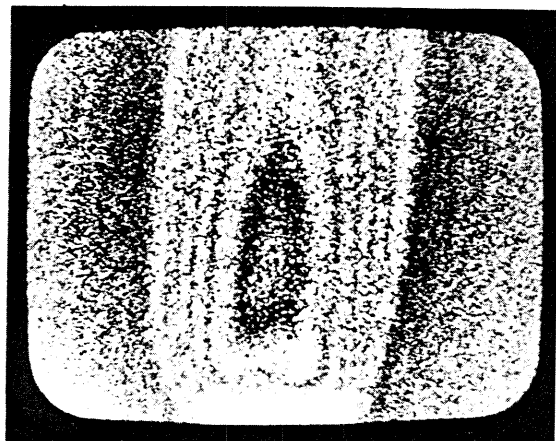In addition mode the fringe visibility is not so high as in the subtraction mode. However,
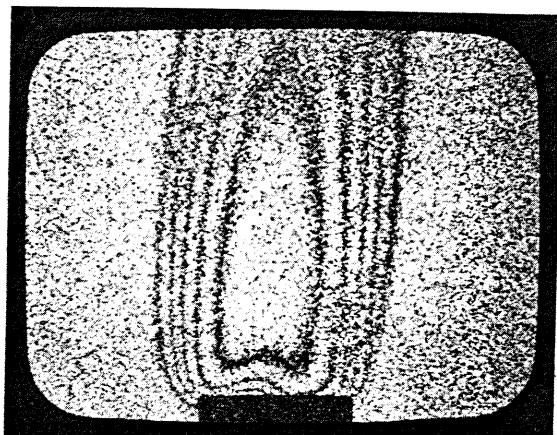
a. Subtraction mode.
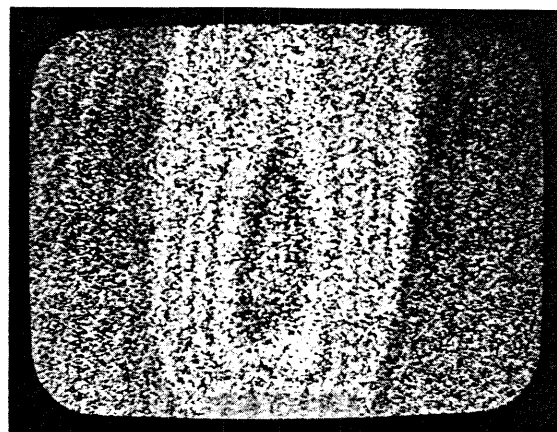
b. Addition mode.

c. Normalizing subtraction mode.

d. Normalizing addition mode.

Fig. 4 ESPI fringes of a town-gas flame.

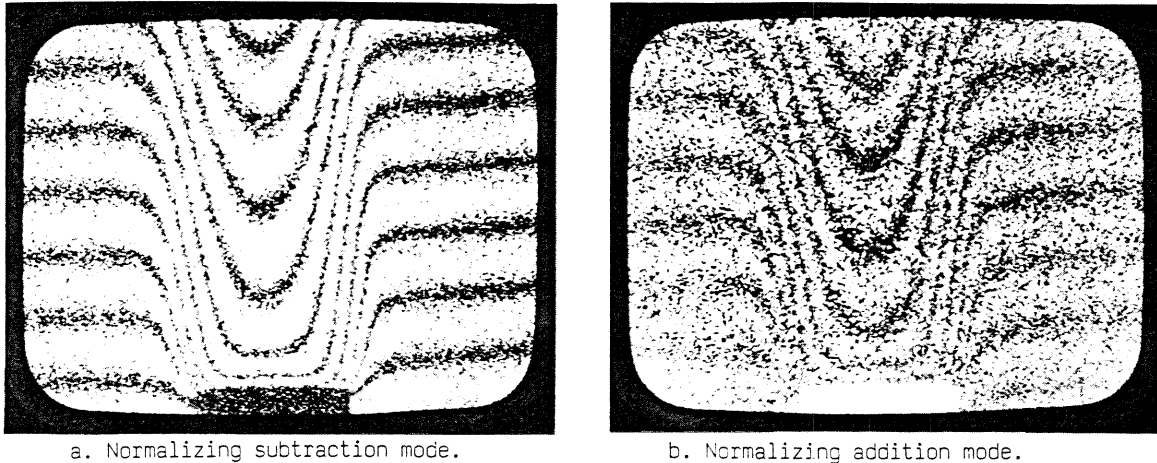a. Normalizing subtraction mode.

b. Normalizing addition mode.

Fig. 5 ESPI fringes of a town-gas flame with tilt.

it is useful for measurements of transient phenomena using a double pulsed laser. Data of two speckle interference patterns must be added on the face of the sensor, for the framing time of usual TV cameras is 1/30sec longer than the interval of laser pulses, that is, they cannot be separately stored in the memory. The independent intensity data of the object and the reference light are also stored when the phenomena do not occur.

In the simple subtraction or addition modes, since the results are multiplied by $4\sqrt{I_o I_r}$, the phase and the visibility of fringes are influenced by the inhomogeneity of the object light and the reference light. The effects can be eliminated by normalizing with $4\sqrt{I_o I_r}$.

Experiments and Results

This methods was examined for the flame of town gas. The above mentioned ESPI system in Fig. 1 and Fig. 2 was used. The data of (1) to (3) were stored when the gas was turned off and the data of (4) were stored when the gas burned. The calculations shown in Table 1 were carried out and their absolute values were displayed on the TV monitor as shown in Fig. 4.

In the subtraction mode clearer fringes appeared than in the addition mode as pointed out above. Normalizing seems to be more effective in the addition mode. As shown in Fig. 5, the background fringes can be added to help us read the phase of fringes correctly by tilting the mirror reflecting the object illumination.

PARTICLE CHARACTERIZATION BY INTERFEROMETRIC PHASE VISUALIZATION

In non-contacting particle measurements in-line holography has played an important role. There are two methods for obtaining the information of particles, one is to reconstruct their real image optically and another is to calculate them from the diffraction pattern. In the former the errors are introduced by aberration tion, diffraction limited imaging and speckle noise. In the latter, since the diffraction patterns depend on the object shape, size, and position, there are difficulties to extract each factor separately and it is difficult to measure the light intensity data accurately from the

photographic record of the diffraction pattern.

To escape from such problem, we propose a new method [3] in which the phase information of the diffraction pattern is visualized in the form of interference fringes. In this method the interfernce pattern is generated by superposing the reference wave on the the diffraction wave, whose intensity data are processed by a computer. The feature of this method is that the size and position factors are separated and the noise produced by the coherent illumination is suppressed by subtraction. The accuracy can be expected to be greatly improved.

Principle

Assume the particle to be opeque and let the two-dimensional cross-sectional shape be $d(\xi,\eta)$. The transmittance is given by

$$t(\xi,\eta) = 1 - d(\xi,\eta). \qquad (9)$$

The complex amplitude of the Fraunhofer diffraction patten of the particle illuminated by a plane wave propagating in the z direction is given by

$$u(x,y) = \exp(ikz)[1+\frac{ik}{z}\exp\{\frac{ik(x^2+y^2)}{2z}\}$$
$$\cdot D(\frac{x}{\lambda z}, \frac{y}{\lambda z})], \qquad (10)$$

where D is the Fourier transform of d. In addition, ξ and η are the object plane coordinates, and x and y are the sensor plane coordinates.
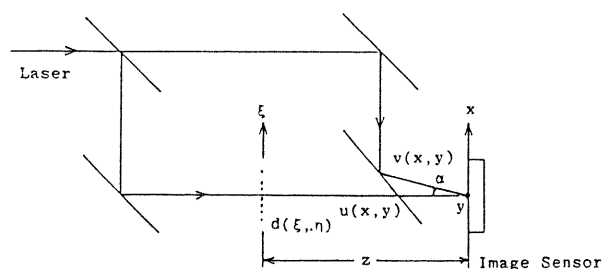

Fig. 6 Setup for interferometric phase visualization of the diffraction pattern.

The intensity is given by the square of Eq. (10),

$$I(x,y) = 1 - \frac{2k}{z} \sin \frac{k(x^2+y^2)}{2z} \; D(\frac{x}{\lambda z}, \frac{y}{\lambda z})$$
$$+ \frac{k^2}{z^2}|D(\frac{x}{\lambda z}, \frac{y}{\lambda z})|^2 . \tag{11}$$

Usually this intensity has been used as data, in which the size, shape and position factors of particles cannot be discminated each other.

Then, if the reference wave incident at an angle α,

$$v(x,y) = \exp\{ik(x\sin\alpha + z\cos\alpha)\} \tag{12}$$

is superposed on $u(x,y)$ as shown in Fig. 6, the interference fringes modulated by the diffracted wave is generated. The interference fringes must have a spacing resolvable by the image sensor. The intensity of the interference pattern is given by

$$I_1(x,y) = 2 + 2\cos[k\{x\sin\alpha + z(\cos\alpha - 1)\}]$$
$$- \frac{2k}{z} \sin[k\{\frac{x^2+y^2}{2z} - x\sin\alpha - z(\cos\alpha - 1)\}]D(\frac{x}{\lambda z}, \frac{y}{\lambda z})$$
$$- \frac{2k}{z} \sin\{\frac{k(x^2+y^2)}{2z}\}D(\frac{x}{\lambda z}, \frac{y}{\lambda z}) + \frac{k^2}{z^2}|D(\frac{x}{\lambda z}, \frac{y}{\lambda z})|^2 . \tag{13}$$

Another interference pattern when the particles do not exist is also used. Its intensity is given by

$$I_0(x,y) = 2 + 2\cos[k\{x\sin\alpha + z(\cos\alpha - 1)\}] . \tag{14}$$

The difference of (13) and (14) is represented by

$$\Delta I_{01}(x,y) = -\frac{4k}{z} \cos[k\{\frac{x^2+y^2}{2z} - \frac{x\sin\alpha + z(\cos\alpha - 1)}{2}\}]$$
$$\times \sin[k\{\frac{x\sin\alpha + z(\cos\alpha - 1)}{2}\}] \; D(\frac{x}{\lambda z}, \frac{y}{\lambda z})$$
$$+ \frac{k^2}{z^2}|D(\frac{x}{\lambda z}, \frac{y}{\lambda z})|^2 , \tag{15}$$

in which the argument of cosine includes the position factor, and the Fourier transform term includes only the shape and size factors. However, if the particle is unsymmetrical, the argument of cosine includes also the shape factor. The last term is negligibly small.

If the data of Eqs. (13) and (14) are taken by an image sensor, stored in a memory and processed by a computer, and the results Eq. (15) are displayed, we can see the phase of the diffracted wave in the processed interference pattern and discriminate the factors of size and position of particles.

Experiments and Results

The fundamental experiments were carried out on static particles by this method using the above mentioned system shown in Figs. 1 and 6.

Data processing soft ware were developed for each measurement and some experiments were made.

Noise reduction. First of all, the usefulness of the subtraction by computer-based processing in the noise reduction should be noted. Fig. 7a is the diffraction pattern of a particle on which the reference wave is not superposed. Fig. 7b is the processed pattern of Fig. 7a subtracted by the pattern when there is no particle and added by the average. Fig. 7a has a lot of noise, but in the processed pattern of Fig. 7b the noise reduces enough to see the concentric ring pattern far from the center whose intensity variation cannot be observed in Fig. 7a. If the processed diffraction pattern is printed as an in-line hologram, the reconstructed image will have less noise.

Phase visualization of the diffraction pattern. We examined the interferometric phase visualization for particles whose diffraction pattern is shown in Fig. 8a. The interference patterns represented by Eqs. (13) and (14) are shown in Figs. 8b and 8c. Their difference added by the average and the absolute value of their difference are shown in Figs. 8d and 8e. In Fig. 8d the phase of fringes jumps by π where they cross each other as expected from Eq. (15) while the fringes of absolute value in Fig. 8e have no phase-jump. They are composed of the linear fringes, the circular fringes like the Fresnel fringes and the circular vague fringes are observed in the figure. They correspond to

a. Unprocessed.
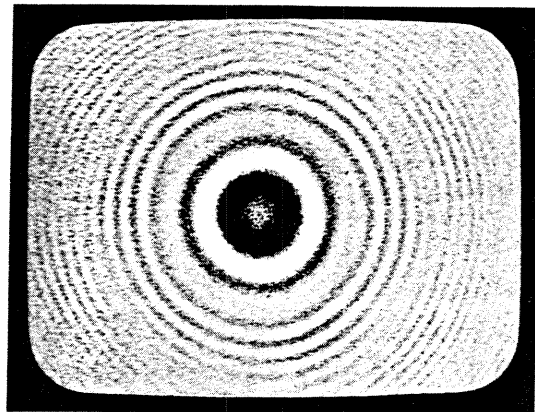
b. Noise reduction by subtraction.

Fig. 7 Diffraction pattern of a particle.

$$\sin\left[\,k\left\{\frac{x\sin\alpha + z(\cos\alpha - 1)}{2}\right\}\right] = const.$$

$$\cos\left[k\left\{\frac{x^2+y^2}{2z} - \frac{x\sin\alpha + z(\cos\alpha - 1)}{2}\right\}\right] = const.$$

and $\quad D(\frac{x}{\lambda z}, \frac{y}{\lambda z}) = const.$, $\qquad$ (16)

respectively. Two sets of concentric circular

fringes have different centers. The distance of the particles to the image sensor can be known from their separation. The size of the particles can be known from the the third set of fringes. In Fig. 9 the results are plotted with the particle size and position measured by this method against those measured with a microscope and a rule.
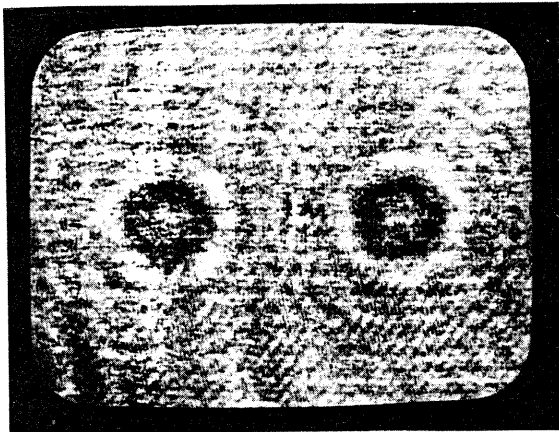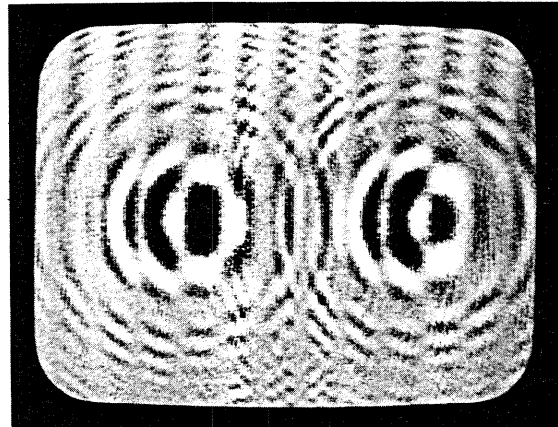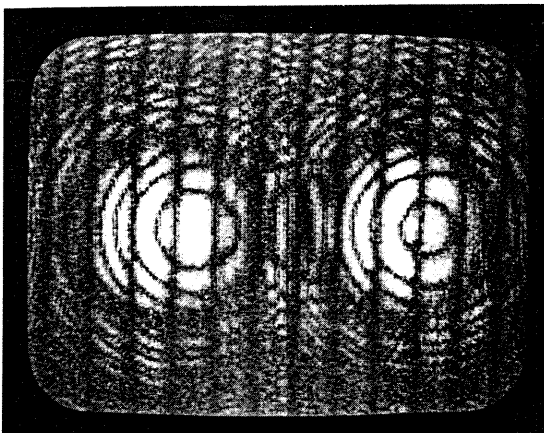

a. Diffraction pattern.
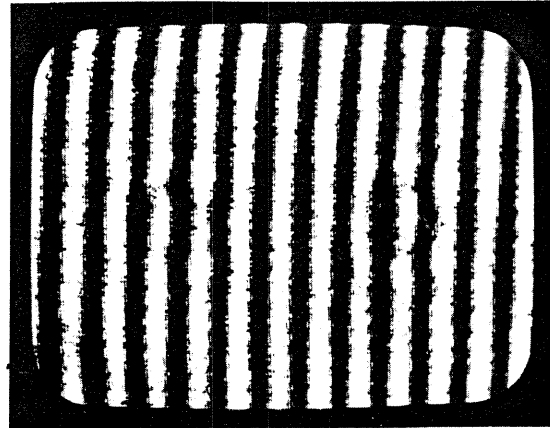
b. Interference fringes with the object.
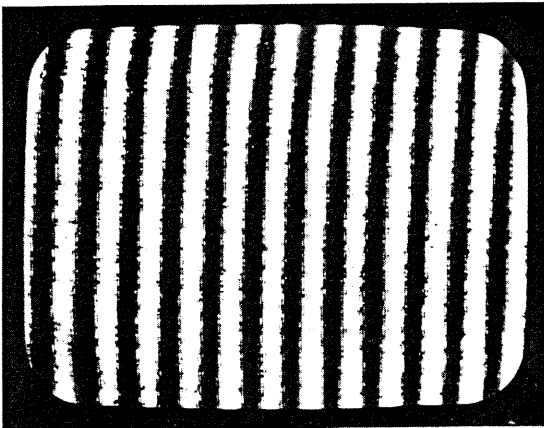
c. Interference rringes without the object.

d. The difference of (b) and (c) + the average.

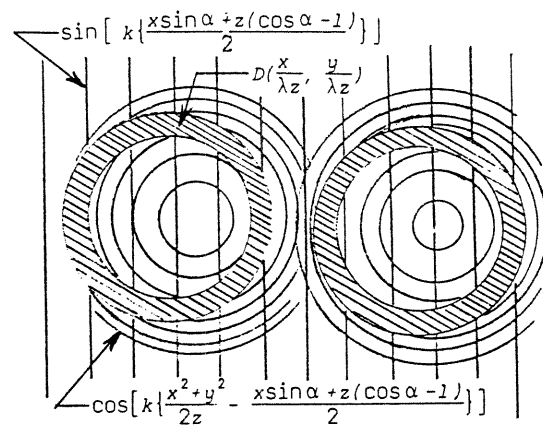e. The absolute value of the differnce of (b) and (c).

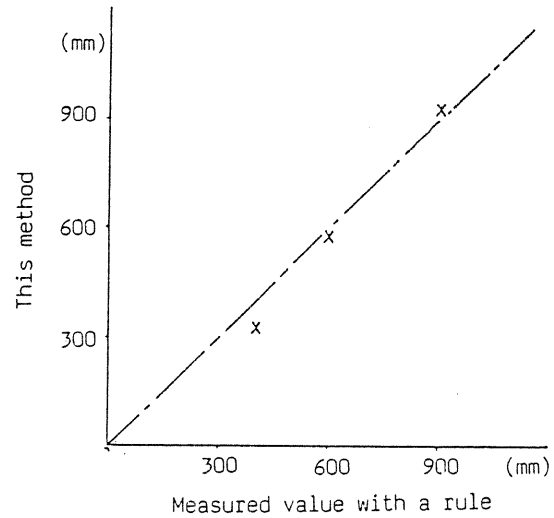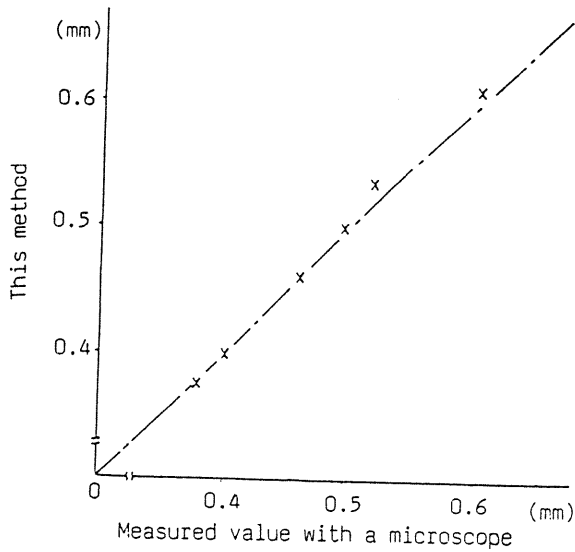Fig. 8 Interferometric phase visualization of the diffraction parrern of particles.

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Fig. 9 left: Particle size.
.right: Distance between the particle and the sensor face.

CONCLUSIONS

Computer-based new interferometric methods for the particle characterization and the refractive index distribution measurements relating to the combustion field were proposed and verified by experiments using an electronic optical data processing system composed of a CCD image sensor, a frame memory and a 16-bit microcomputer. The results lead to the following conclusions.

(1) In the index measurement by electronic speckle pattern interferometry four methods were examined. By the subtraction mode clearer fringes generated than by the addition mode. The normalizing method was effective for suppression of the noise especially in the addition mode. We have a prospect that the computer-based ESPI may take the place of holographic interferometry, since the results can be obtained in real-time and without troublesome procedures.

(2) By computer-based processing the interference fringes produced by superposing the reference wave on the diffraction pattern, the phase of diffraction patterns can be visualized and the fringes relating to the size and position factors of particles are generated separately. This method was verified by the experiment carried out on particles. The accuracy can be greatly improved compared with the methods using photographic materials such as in-line holography and the results can be acquired in real-time.

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