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A METHOD FOR TRANSIENT DENSITY FIELDS MEASUREMENTS

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ABSTRACT

Effects of spherical aberrations of the mirror used in the moire system on the angular resolution of the system are investigated. It is shown that the spherical aberrations may reduce significantly the performance of the conventional moire deflectometer. However, due to the heterodyne procedure, this is not the case with the heterodyne moire system. A moire system with a constant speed moving grating is demonstrated. It is shown that the system readout is linear and the system does not need calibration. In addition, the repeatability of the measurements is improved in this system as compared to the sinusoidally moving grating setup. The problem of the photographic plates alignment is solved by using a mechanical system in which the plate is held firmly throughout the experiment and accurately replaced after removing for photographic processing. The effect of a circular detector's aperture size on readout was tested. It is shown that the spatial phase variations, observed when scanning along a straight moire fringe, may considerably be reduced. At present we may say that both the on-line and the deferred heterodyne moire techniques may reliably be used. The errors of phase readings are 1° and 5° for the on-line and deferred methods. The total error due to subtraction of two readings at each position is, therefore, 1.4° and 7°, respectively. Further research for improving the deferred system is suggested.

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FIGURE CAPTIONS

I. INTRODUCTION

The heterodyne moire deflectometry[1-5] is a conceptually simple and potentially very accurate and sensitive method for measuring deflection angles of light rays. The heterodyne moire method has been studied extensively both theoretically and experimentally in two modes of operation, namely the on-line mode[1-3] and the deferred mode[4-5]. The on-line mode is used for steady state density fields where the analysis of the whole field may be completed in real time, thus no photographic techniques are needed to store the phase object. It has been shown that the on-line technique can be used reliably for density gradient measurements. When unsteady phenomena occur, or when it is difficult to complete the analysis of the field in real time, the deferred mode of operation is applied. In this case, the shadow of the phase object, illuminated through one Ronchi grating is recorded photographically for later readout.

The basic idea of the on-line heterodyne technique is to measure the phase of the signal from a photodetector detecting the light transmitted through a travelling moire fringe pattern. The moving fringes, in the previous experiments, were generated by vibrating the output Ronchi grating sinusoidally relative to the first grating. The vibrations were accomplished by attaching the grating to an electromagnetic shaker. When collimated light is not disturbed by the phase object (straight line fringes), the first harmonic of the photodetector signal is approximately given by[2]

$$I\ (y,\Delta^*,t) = \frac{2}{\pi^2}\cos(\pi\Delta^*)\cos[2\pi(\frac{\chi}{p} + \frac{y\theta}{p} + \frac{\Omega}{2\pi}\ t)] \qquad (1)$$

where $\Delta^* = \Delta/(p^2/\lambda)$ is the distance between the gratings in Fourier units and χ/p and $y\theta/p$ are phase shifts related to the relative translation and rotation of the Ronchi gratings. Here χ is the x-directed offset between the lines of the two gratings. Ω is the fundamental frequency of the signal. p is the pitch of the gratings.

The effect of refraction by a phase object is to introduce a phase shift

$$\Delta\psi(r) = 2\pi \frac{\phi_x(r)\Delta}{p} \quad , \tag{2}$$

where $\phi_x(r)$ is the angle of refraction in the x-direction at a point $r \equiv x, y$. A procedure for measuring this phase shift is to record the electronic phase relative to that of a reference signal, with and without the phase object, and subtracting the two phases. The properties of the phase object are then computed by the density gradient-refraction angle relations[2].

In the case of the deferred moire, the second Ronchi grating is replaced by a photographic plate. The phase object is recorded on the photographic plate by exposing it to the collimated beam transmitted through the phase object and the first grating, thus the distorted image of the first grating due to refraction by the phase object is recorded. Readout is accomplished by placing the moving grating immediately in back of the processed photographic plate. When the combination is illuminated, a time varying signal is obtained and the phase shift is measured by the heterodyne technique. To obtain the absolute fringe deflections, the phases of the undisturbed fringes have to be measured. This is done by exposing a second photographic plate to the collimated beam when the phase object is removed. The phases of this plate, referred later to as the reference plate, are measured and subtracted from the phases, measured at the corresponding points, on the object exposed plate.

Experiments which have used the deferred heterodyne moire technique, show that the method is not as accurate and repeatable as the on-line technique[5-7]. The following problems may explain the sources of error:

1. In order to measure the heterodyne phases accurately it is vital to align precisely the two photographic plates (the reference and the object plates) while replacing them between measurements. It is important to keep the x,y offsets and the relative rotation angle as small as 1 micrometer and 1/360 degree, respectively.

   This problem was partially solved by using the two-color double exposure recording technique[8]. This technique enables the two states of the phase object to be recorded on the same film. However, the technique was not evaluated yet with weak phase objects for high accuracy measurements.

   In this work we offer a mechanical solution for the alignment problem.

2. It was observed that as the photodetector scans with respect to x direction, parallel to a straight line moire fringe pattern, the phase varies with spatial period of one grating pitch whereas it is expected to be constant. This effect, which may introduce severe errors to the system has been shown to be due to higher order terms retained in the fundamental harmonic signal component. It has been shown theoretically that this effect can be reduced or even eliminated by using photodetectors with proper aperture sizes and shapes[7]. These results are verified experimentally.

3. The non-linear motion of the grating is undesirable because it leads to non-linear transfer function of the overall instrument and thus to the need for calibration. The calibration procedure, which has to be repeated each time the shaker is turned off and restarted, reduces the accuracy of the method. In the present report we describe a new experimental set-up in which the grating moves with a constant speed.

4. Both the on-line and the deferred moire systems use a spherical mirror for generating the collimated beam. The unavoided spherical aberrations may introduce errors to the system due to imperfect collimation.

In the present work we study the effect of the spherical aberrations on the accuracy of the system. We evaluate the performance of the new system in which the grating motion is linear. The results of the accuracy and repeatability of the mechanical gratings alignment system and the effect of the photodetector aperture on periodical phase variations are presented.

II. SPHERICAL ABERRATIONS

When a large relative-aperture spherical mirror is used for generating a collimated light beam, the rays from a point source at the focal point are not all reflected parallel to the mirror axis but as shown in Fig. 1. This phenomena is referred to as the spherical aberration of the mirror. The relative-aperture of a mirror is defined as the ratio of its size to its focal length. The smaller the relative-aperture is the smaller are the aberrations. The aberrations can be reduced by using high precision mirrors or off-axis paraboloidal reflectors. The use of paraboloidal reflectors is very expensive. Nevertheless strictly parallel light beams can never be obtained in practice because of the finite dimensions of any actual light source, causing some of the rays to come from points off the axis.

It is the objective of the present section to study the effect of the spherical aberration of the mirror used in the moire deflectometer, on the accuracy of the method.

The geometry of the problem is shown in Fig. 2a. The spherical reflector is of diameter D with center of curvature C(0,0,-R), F(0,0,-R/2) is the focal point. The incident ray, with unit vector $\bar{e}(\alpha,\beta,\gamma)$ emitted from F meets the reflector surface at the point $A(x,y,z) = A(x,y,-R+\sqrt{R^2-x^2-y^2})$ and reflects along the direction of the unit vector $\bar{e}'(\alpha',\beta',\gamma')$. The normal to the surface at A is $\bar{\nu}$ given by $\bar{\nu} \equiv \frac{C-A}{|C-A|} = \left(-\frac{x}{R}, -y/R, \frac{-\sqrt{R^2-x^2-y^2}}{R}\right)$. $\bar{e}$ and $\bar{e}'$ make an angle δ with the normal $\bar{\nu}$. The law of reflection, given by[9]

$$\bar{e}' = \bar{e} - 2\bar{\nu}\cos\delta \tag{3}$$

leads to

$$\begin{aligned} \alpha' &= \alpha + 2\cos\delta\,\frac{x}{R} \\ \beta' &= \beta + 2\cos\delta\,\frac{y}{R} \\ \gamma' &= \gamma + 2\cos\delta\,\frac{\sqrt{R^2-x^2-y^2}}{R} \end{aligned} \tag{4}$$

α', β' and γ' may be expressed as a function of (x,y,z), the coordinates of the point A at which the ray meets the reflector, by using the following equalities

$$\cos\delta = \bar{e}\cdot\bar{\nu} \tag{5}$$

$$\bar{e} \equiv \frac{A-F}{|A-F|} = \left(\frac{2x}{R}, \frac{2y}{R}, 1 + \frac{2\sqrt{R^2-x^2-y^2}}{R}\right) \tag{6}$$

The useful part of the reflector for generating the collimated beam is limited to the small circle of radius r, shown in Fig. 2b. Reflections from mirrors larger than r will be disturbed by the focal point light source.

The angles $\theta = \cos^{-1}\alpha'$, $\varphi = \cos^{-1}\beta'$ and $\psi = \cos^{-1}\gamma'$ were calculated, using Eqs. (4), (5) and (6), for different values of r/R. The divergence of the reflected beam i.e. the maximum variation of the angles θ, φ and ψ

over the useful part of the reflector (the mirror of radius r) are given in Table I. From the table it is evident that the beam divergence, due to

Table I. $\Delta\theta$, $\Delta\varphi$ and $\Delta\psi$ are beam divergence angles over the mirror aperture along the x,y and z directions, respectively. r/R is the mirror relative-aperture.

r/R	$\Delta\theta$(deg.)	$\Delta\varphi$(deg.)	$\Delta\psi$(deg.)
0.200	3.315	1.987	3.315
0.100	0.445	0.265	0.445
0.066	0.134	0.079	0.134
0.050	0.057	0.034	0.057
0.040	0.029	0.017	0.029
0.033	0.017	0.010	0.017
0.029	0.011	0.006	0.011
0.025	0.007	0.004	0.007
0.022	0.005	0.003	0.005

aberrations, in the y direction is about half the divergence in the x and z directions. This result suggests that the Ronchi grating lines should be aligned along the x-direction (ray deflections along the grating lines do not affect the moire readings since the measured deflections are in the direction normal to the lines).

The average deflection angle over the mirror aperture in the y direction is $\Delta\varphi/2r$ thus the average deflection over one grating pitch is

$$(\Delta\varphi)_p = \frac{\Delta\varphi}{2r}\,p \tag{7}$$

The angular resolution of the system is given by[2]:

$$(\Delta\varphi)_{min} = \frac{p}{360\Delta} \tag{8}$$

where Δ is the separation distance between gratings.

In order to minimize reading errors, it is desired to keep the ratio

$$\frac{(\Delta\varphi)_p}{(\Delta\varphi)_{min}} \equiv \frac{180\ \Delta\varphi\ \Delta}{r} \qquad (9)$$

as small as possible.

For a typical mirror dimensions r = 10 cm, r/R = 0.04 and $\Delta\varphi$ = 0.017 (from Table I) and for gratings separation of Δ = 20 cm, Eq. 7 yields $(\Delta\varphi)_p/(\Delta\varphi)_{min} = 6$. This result may be interpreted as if the angular resolution of the system is reduced by a factor of 6. However, due to the procedure of the heterodyne technique, this is not the case[2]. The procedure for measuring the phase shift is to record the electronic phase relative to that of a reference signal, with and without the phase object, and subtracting the two phases. This procedure cancels the errors due to spherical aberrations (as well as due to other possible errors resulting from imperfections in other optical components).

III. LINEAR GRATING MOTION

As mentioned before the disadvantage of using an heterodyne moire deflectometer with a sinusoidal grating motion is the need of its calibration. The calibration procedure reduces the accuracy of the system and the simplicity of using it.

In this section we describe a moire system with a constant speed moving grating and study its performance.

A. Experimental Setup

The system consists of a collimated light source, a stationary Ronchi grating G_1 and a moving grating G_2. Two photomultipliers detect the heterodyne signals and a personal computer is used to sample and analyze the data. The gratings have a pitch of p=0.083 mm and the separation between the moire fringes is p'=5.30 mm. The distance between the gratings is Δ= 88 mm. For the deferred mode operation, the second grating is replaced by a photographic plate, and after being exposed and developed the plate is placed in front of the moving grating for heterodyne readout. The schematic of the experimental setup for deferred readout is shown in Fig. 3.

The grating G_2 was translated linearly by mounting it on a constant-speed moving table, shown schematically in Fig. 4. The moving table consists of a ball bearing slide comprised of two basic components, a stationary base and a moving carriage which moves linearly along the base. The motion is very smooth and with high straight-line accuracy. The moving carriage is connected, on one side by a cord to the pulley of a DC motor and on the other side, by a cord over a frictionless pulley to a weight hanging vertically.

The detection system consists of two 0.75 mm fibers, one the reference fiber is fixed and the other, the test fiber, is movable. The fibers are connected to photomultipliers which are fed through an A/D interface board into a personal computer for data acquisition. Typical signals are shown in Fig. 5. The frequency of the signals is 284 Hz. The phase between the reference signal and the test signal are calculated by zero crossing and Fourier methods. The two calculation methods agree within 0.3 degree. The phase difference of the signals shown is 320.6°.

The A/D conversion is triggered by an electrical pulse generated by a silicone phototransistor coupled to a galium arsenide infrared emitting diode. The pulse is initiated at the instant the moving carriage arrives at a certain position where it interrupts the infrared and thus switching the phototransistor output from an "on" to an "off" state.

B. Calibration

The present heterodyne moire system was calibrated by the same procedure as that followed in Ref. 2, i.e. the electronic phase vs. the distance of the test fiber from the moire fringe was plotted. A typical calibration curve is shown in Fig. 6. In order to check the repeatability of the readings, the phase at each fiber location was measured twice. The difference between readings did not exceed two degrees. From the figure it can be seen that the calibration curve is linear, as expected. This result is very important since it indicates that no calibration is required when the second grating motion is linear.

IV. ERROR SOURCES

A. Photographic Plates Alignment

One of the major requirements of the deferred moire system is the precise alignment of the two photographic plates corresponding to the reference and phase object deflectograms. In the present work the alignment problem was solved by a mechanical system in which the photographic plate can be held firmly in the same place throughout the whole experiment (exposure, development, replacement and analysis). The mechanical system, shown schematically in Fig. 7, consists of two parts: the plate carriage and the carriage holder. The carriage is made of stainless steel which is impervious to all photographic processing chemicals. The photographic plate is held firmly to the carriage by means of finger springs.

The carriage is attached to the carriage-holder by means of a spring, which secures the carriage to a reference plane defined by three points of contact. The carriage can easily be removed and precisely replaced.

The alignment precision was tested as follows: the phase ϕ between the reference and the test signals was measured (experimental setup described in Sec. III), $\phi=156^\circ$. While keeping the two detectors at the same fixed positions the carriage (with the Ronchi grating) was removed and replaced. The phase was measured again, $\phi=153^\circ$. This procedure was repeated several times, the results are summarized in Table II.

Table II. Phases measured after removing and replacing the grating from the system.

measurement no.	1	2	3	4	5	6	7	8
phase (deg)	153	152	154	162	161	157	150	164

From the table, the average phase and the standard deviation were calculated to be 157° and 5°, respectively. The same experiment was repeated several times but with the detectors at different positions. Similar results for phase scattering were obtained.

It has been noted that while the plate-carriage is removed or replaced, the holder is slightly moving. This is as a result of the mechanical pressure exerted on the holder by hands. The effect of this pressure on the measurements scattering was tested. The testing procedure was the same as described before but in this present experiment the holder was delicately banged between measurements while the carriage stayed in position. A standard deviation of 2.5° was found as compared with about 1.5° when successive measurements were taken without touching the system.

The experiment indicates that the measured standard deviation of 5° can be reduced by improving the holder and by using higher quality Ronchi gratings.

B. Photodetector Size Effect

It has been theoretically shown that the periodical phase variations observed as the detector scans parallel to a straight moire fringe, depends on detector size and shape[7].

In the present work, the effect of the size ρ of a circular detector was studied. Two values of ρ/p were tested: $\rho/p=3.1$ and $\rho/p=9.3$. Both cases show phase variations with spatial period of one grating pitch. With $\rho/p=3.1$ the peak-to-peak variations are 13°. This result is in agreement with theory and repeats the previous experimental results[6]. Heterodyne scan of the moire fringe pattern parallel to the unshifted fringe with $\rho/p=9.3$ detector is shown in Fig. 8. The peak-to-peak phase variation is nearly 3° or 1/120 fringe. The results are consistent with theory. More experiments, which will also include square aperture detectors are planned.

V. SUMMARY

To summarize the project we may say that at present both the on-line and the deferred modes of the heterodyne moire deflectometer can be reliably used for accurate and sensitive measurements of phase objects.

Theoretically it was shown that the performance of the deferred mode is the same as that of the on-line mode due to the fact that accuracy and sensitivity of the system are weakly affected by non-linear photographic emulsion characteristics.

However, practically the deferred mode encountered some problems which reduced its accuracy, namely the alignment problem and the phase variation along straight line moire fringes. Those problems were solved, and at present an accuracy of $\pm 5^\circ$ in phase measurement has been achieved in the deferred mode.

Also, the non-linear grating motion problem was solved. At present a constant-speed grating motion is used, thus the system does not need calibration and in addition the accuracy and reproducibility of the measurements has been improved.

The accuracy of the heterodyne moire deflectometry can further be increased by improving the mechanical stability of the plate holder and by using higher quality Ronchi gratings. It is also desirable to improve the two-color double exposure photographic recording technique as a part of the effort of increasing the performance of the system.

It was shown that the spherical aberrations of the mirror used, as a part of the collimated light source, may reduce significantly the angular resolution of the conventional moire deflectometer. However, due to the measurements procedure of the heterodyne technique this is not the case in the heterodyne moire system.

For future studies it is proposed to investigate the following related subjects:

1. MTF measurements by moire deflectometry. This includes the investigation of the effects of turbulence on fringe contrast and on the electronic readout.
2. It is suggested to continue and study the use of the moire technique for 3-D phase objects.

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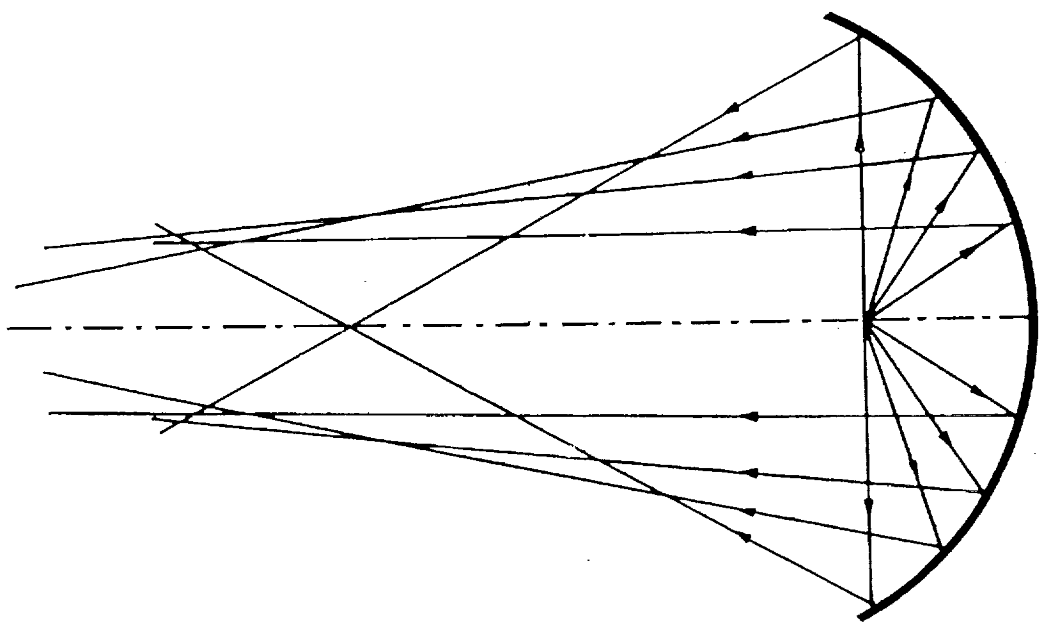


Fig. 1: Spherical aberration of rays from the focal point of a mirror of large aperture.

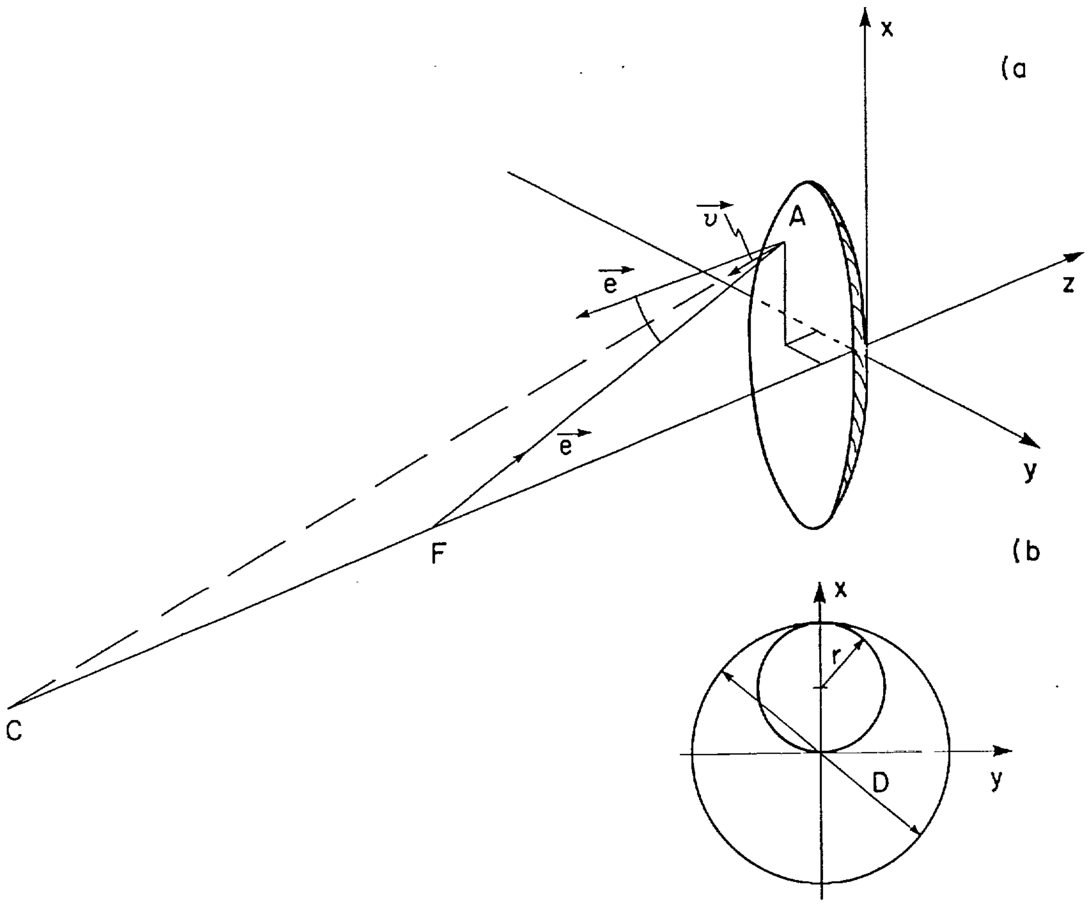


Fig. 2: Reflection at a spherical mirror.
(a) Coordinates of rays geometry.
(b) Front view of the mirror.

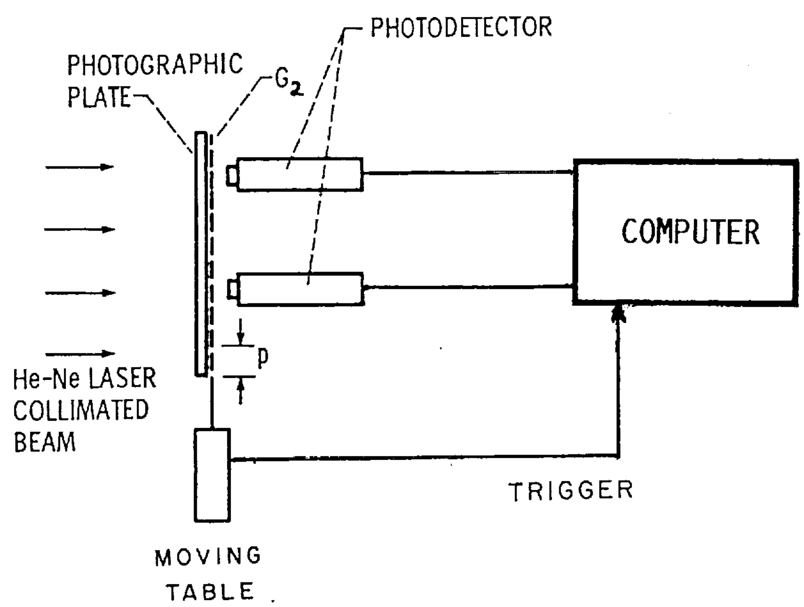


Fig. 3: Schematics of the experimental setup.

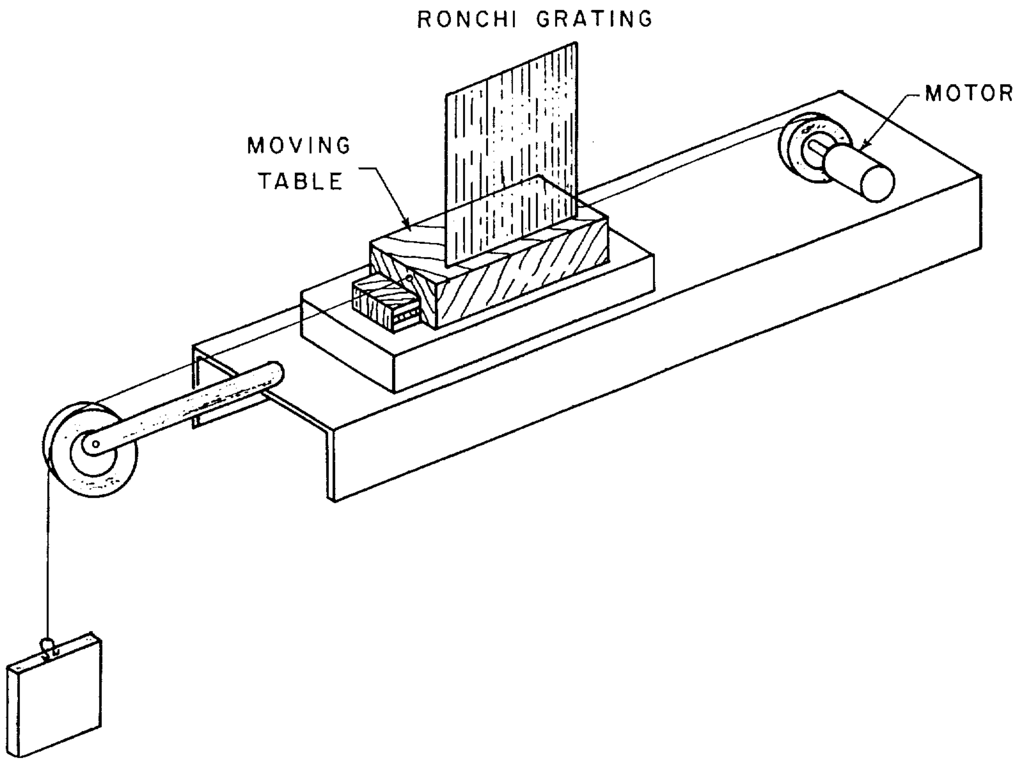


Fig. 4: The constant speed moving grating system.

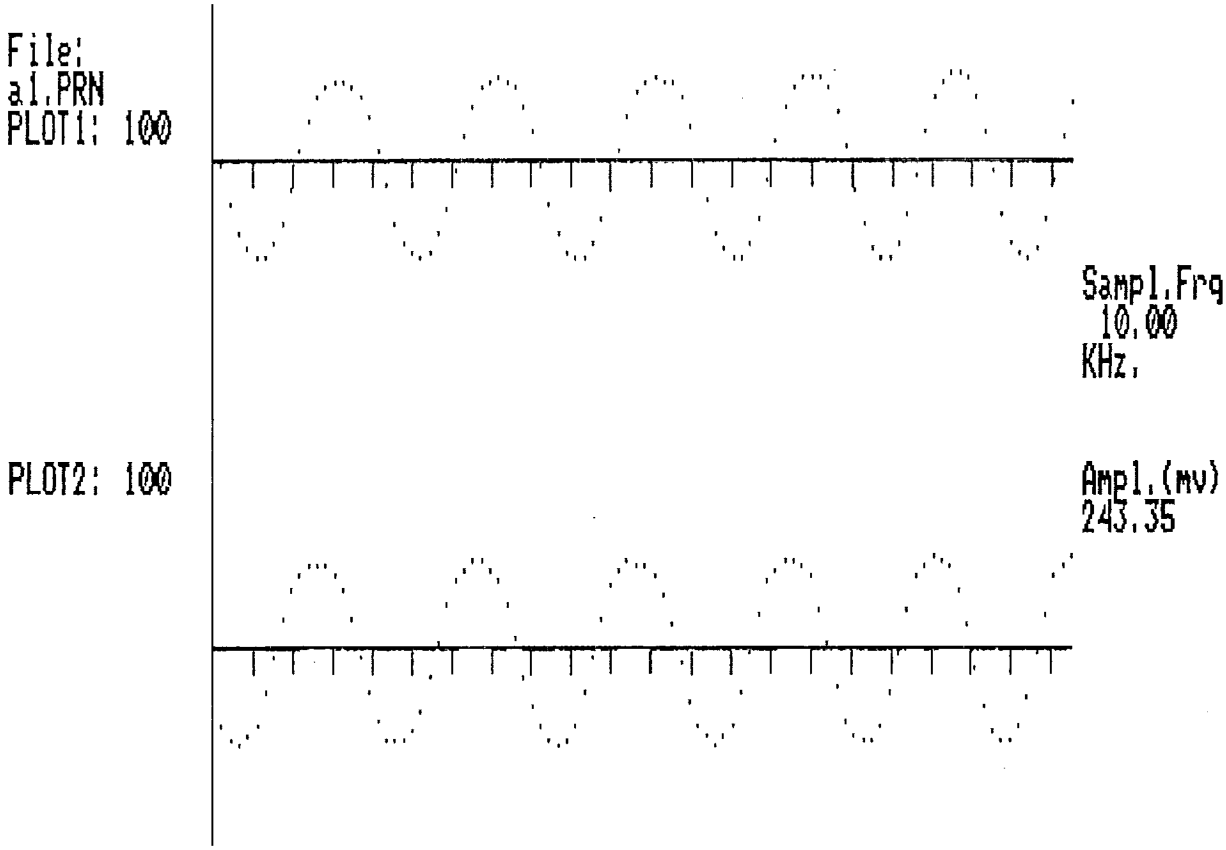


Fig. 5: Typical sampled signals. The upper curve is the test signal and the lower curve is the reference signal.

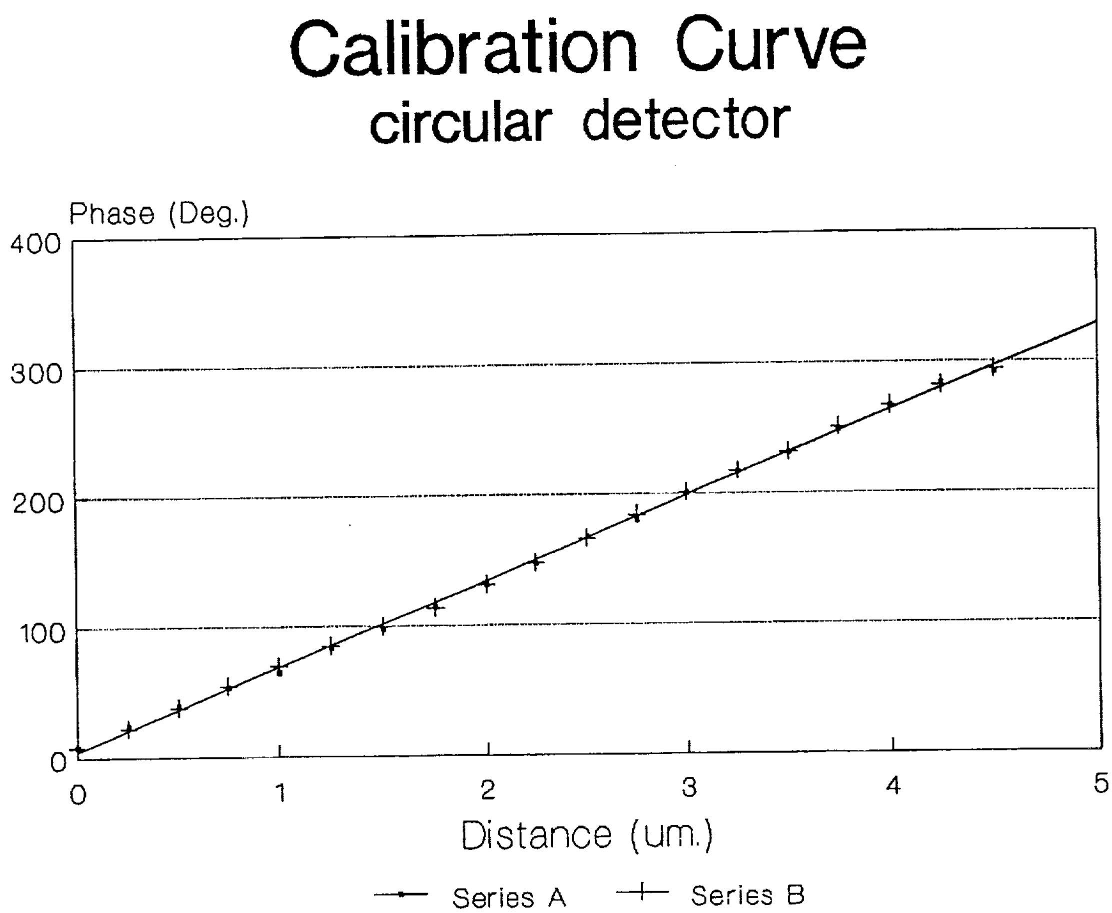


Fig. 6: Calibration curve.

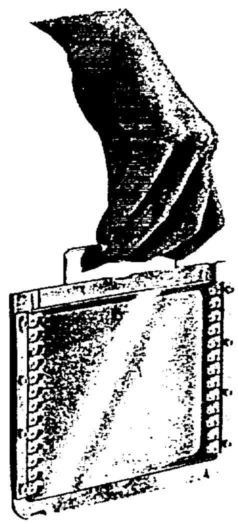
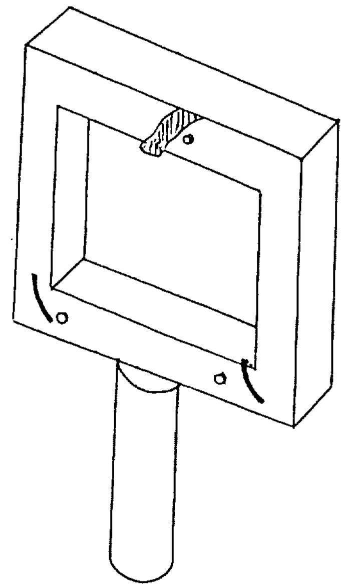


PLATE CARRIAGE



CARRIAGE HOLDER

Fig. 7: Plate holder for deferred moire deflectometer.

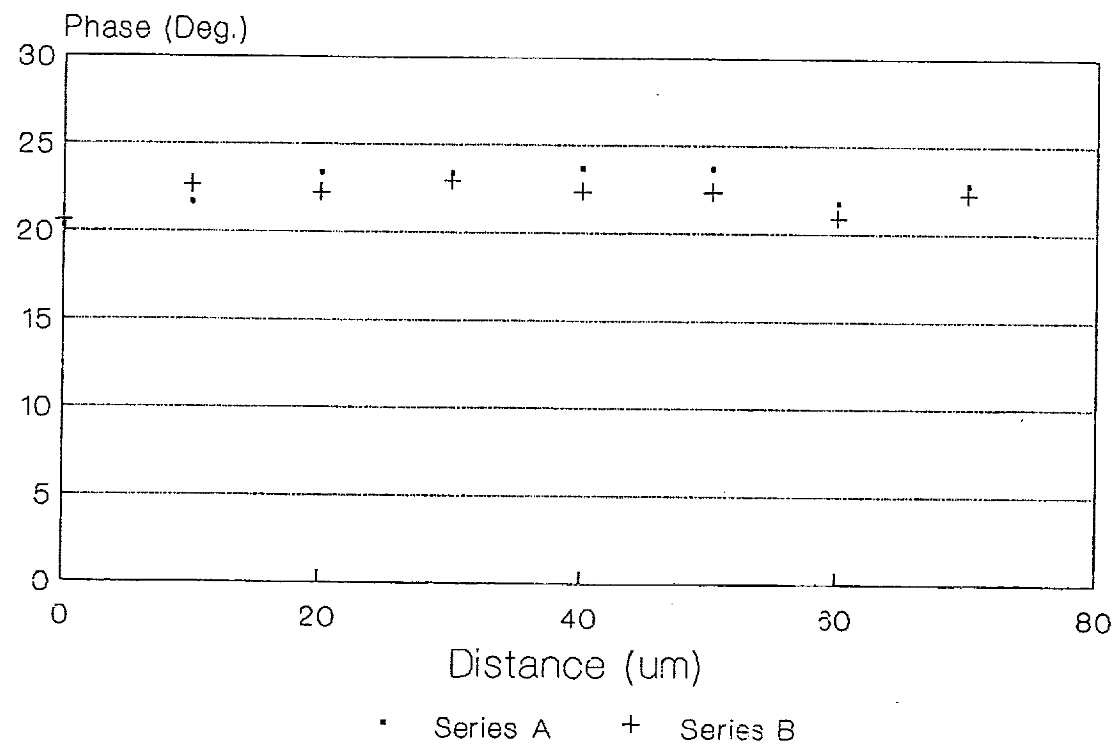


Fig. 8: Heterodyne scan of a moire fringe pattern parallel to unshifted fringe. $\rho/p=9.3$.