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SLOTTED APERTURES FOR MULTIPLEXING GRATING FREQUENCIES AND SHAR--ETC(U)
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SLOTTED APERTURES FOR MULTIPLYING GRATING FREQUENCIES AND SHARPENING FRINGE PATTERNS IN MOIRE PHOTOGRAPHY

METALS BEHAVIOR BRANCH
METALS AND CERAMICS DIVISION

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Slotted aperture filter masks can be used to "tune" a photographic system to an integral multiple of a fundamental grating frequency. Such a procedure can be used in moire photography for multiplying sensitivity and for obtaining improved rendering of fringe patterns. Depth of field is increased, and a camera lens of poorer quality than is normally required for high resolution photography of moire gratings is adequate. Also gained is flexibility in optical data processing of moire photographs and in the use of two-dimensional grid and dot specimen airays.

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FOREWORD

This technical report was prepared by the Metals Behavior Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The research was conducted by Dr. Gary Cloud under work unit directive 22790101 during the period March 1976 - June 1976.

This research was conducted while the author was a senior resident associate of the National Research Council. The support of the NRC and the Air Force Materials Laboratory is deeply appreciated.

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SECTION I

INTRODUCTION

Forno(1) and Burch and Forno(2) have demonstrated that slotted apertures can be used to tune a camera lens to give sharpened photographs of grating structures, improve depth of field, and enhance the response of a photographic system to certain spatial frequencies which might be contained in a random pattern. The potential applications of such procedures, which are based upon well known principles of optics, are many.(3) The work of Burch and Forno seems directed mainly towards measurement of deformation and strain through elegant but simple improvements of the moire and speckle techniques.

This report describes an extension of the concepts which are developed and utilized in the references mentioned above. Slotted camera apertures can be used for multiplication of grating spatial frequency in moire photography. Sensitivity of the measurement, which is often a serious problem when measuring strains with the moire method, can be increased several fold. Depth of field is increased, and a camera lens of ordinary quality can be used to photograph the high frequency gratings. The method gives improved photographic rendering of grating lines when sensitivity multiplication is not needed. The photography of two-dimensional arrays (grid and dot patterns) is simplified. These improvements are apart from any gains which are derived from coherent optical processing of the moire photographs by the methods which were developed and described in detail by Post,(4,5) Post and McLaughlin,(6) and Chiang.(7) It is important to note that the sensitivity enhancement which may be realized through improved grating photography can be amplified by appropriate optical processing to yield an overall multiplication which is greater than that which would result from either method used alone.

SECTION II

PROBLEM AND CHOICE OF METHOD

1. REQUIREMENTS

The study described below resulted from a requirement to measure the displacement and strain fields around fastener holes which are cold worked with a mandrel. Both elastic and plastic strains were to be measured, so it was desirable to incorporate some control of sensitivity into the test procedure. Whole-field measurements were needed. These requirements and others imposed by available facilities seem to be satisfied best by the moire technique with optical processing of the data. The presence of out of plane displacements in the deformation field eliminated methods of direct superposition of master and specimen gratings. Direct photography of the deformed and undeformed specimen gratings seemed to be the simplest approach to the problem. The photo plates of the deformed and undeformed gratings can be superimposed to obtain the moire fringe pattern. It was natural with this approach, however, to utilize the sensitivity multiplication and pitch mismatch capabilities which can be derived from superposition of the specimen photo plates with master gratings of higher spatial frequency in an optical processor.

For this procedure to work well, it is generally best to have specimen grating photographs and master gratings which are sharp and of high contrast. In the past, gratings of low spatial frequency were used and lenses of best quality were required for grating photography (or for optical superposition at the camera back if that alternative was employed). These requirements are relaxed if appropriate spatial filter apertures are used in the grating photography stage. The same ideas are useful where it is necessary to make high frequency grating submasters by photographing a master grating.

2. SPECIMEN GRATINGS

In our experiments, gratings of frequency 39 lines per mm (1000 lines per inch) were applied to the specimen using ordinary photoresist techniques. The master grating, which was supplied by Photolastic Inc., was of rather poor quality in that it exhibited gross transmittance variations over its extent in addition to numerous pinholes and other flaws. The photoresist was Shipley 1350-J, which worked well even under less-than-optimum coating and exposure conditions. The photoresist was exposed through the master grating at a distance of 15 cm from the 100 watt mercury lamp contained in a Visicorder. This lamp has a very small arc, so the resist could be brought close to it without loss of definition in a measure to compensate for the low lamp power. Even so, exposures had to be much longer (about 10 minutes) than is considered acceptable for complete exposure of the photoresist. As a result of these equipment and processing deficiencies, the specimen gratings were far from perfect. A typical example is shown magnified in Figure 1a. Figure 1b shows the extent to which the resist coating is damaged in regions of large plastic deformation near the fastener hole. Even with the obvious flaws, it proved possible to photograph the specimen gratings in reflected light without special apertures. The resulting moire patterns were useable, except that fringe definition was seriously degraded in the regions of high plastic deformation where the resist coating was damaged. With slotted apertures, the specimen gratings proved sharp enough so that emphasis of the second harmonic with a properly tuned lens produced specimen gratings photos equivalent to 80 lines per mm (2000 LPI), which is the highest frequency harmonic theoretically obtainable with the lens used.

3. GRATING PHOTOGRAPHY

The camera available for this study was a Burke and James "Orbit" 4x5 view camera with an f9 Goerz "Red Dot Artar" lens of 241 mm (9½ inches) focal length. This camera was stiffened with angle iron and the photographic setup mounted on a Gaertner optical table. The camera was moved as close as possible to the specimen giving a photoimage magnification of 1.3. This use of magnification reduces the frequency response demands on the photo system and, when properly exploited, leads to an increase of measurement sensitivity.

The specimens were illuminated in diverging white light from a Kodak 35 mm slide projector which contains a quartz-halogen lamp. Angle of incidence of the light is somewhat critical, with 30° being an approximate optimum value. Grating contrast was improved slightly by using lighting from only one side of the camera. The price for this improvement is uneven illumination, and a small amount of "dodging" was required to produce photo plates of uniform density.

Kodak High Resolution Plates and Kodak 649-F Plates were used for recording grating images. Both worked well. The results reported here were obtained with the 649-F material. Kodak D-8 developer, which is a high-energy, high-contrast type, was chosen after trials of several others. This developer is very fast and control of exposure and development time and temperature are somewhat critical. It was found that some deviation from optimum exposure and processing values could be compensated in the optical data processing stage

A micrograph of a typical photograph of a specimen grating, taken at f11 in white light without any sort of optical filtering, is reproduced in Figure 2. Grating frequency in the film is 30 lines per mm (762 LPI). Negative photos of this sort were used extensively in our moire studies. Single exposures may be superimposed with one another to produce observable fringes. They have been used in various combinations in the optical filtering set up. While double exposure plates produced barely observable fringes, the patterns were clear when they were observed in the data processor, and, in fact, higher order patterns with the appropriate fringe multiplication could be observed.

4. SLOTTED APERTURES

Forno(1) summarizes information required to design slotted aperture filter masks which will tune a given camera for photographic emphasis of particular space frequencies. These same principles can be used to obtain photographs containing gratings having frequencies which are multiples of the fundamental frequency in the specimen grating if (1) the higher frequencies are present in the structure being photographed and (2) the camera and film are capable of responding to those frequencies. The practical significance of requirement (1) is that the specimen grating be sharp and of high contrast--that is, it should resemble a ruling more than a simple sine grating. The limits imposed by condition (2) are easily calculated for any camera-film combination.

Slotted apertures were designed to fit behind the iris diaphragm inside the Goerz lens. Slot sizes and locations were calculated to tune the lens to spatial frequencies of 30 and 60 lines per mm in the image plane for green light (corresponding to 1000 and 2000 LPI in the specimen plane). Since the masks were to be placed near the iris, it was necessary to account for magnification of the mask by the rear lens element. This magnification was found to be 1.09.

In establishing a slot width, which governs the bandpass of the tuned lens, it is necessary to account for the maximum and minimum grating frequencies which will be encountered in the photography of the strained grating. Our masks were designed for a fairly broad bandpass, giving a strain response of more than ±10%.

Dimensions of the two masks used are shown in Figure 3. The results reported here were obtained with apertures which were cut from cardboard with a pocket knife.

SECTION III

TYPICAL RESULTS

Figure 4 shows micrographs of typical photoplates of the same specimen used for Figure 2 but taken with the apertures installed in the camera lens.

Comparison of Figures 4a and 4b, which were recorded with the 30 lines per mm mask (referred to image plane) with Figures 1a, 1b, and 2 suggests the degree of improvement which can be expected from using filter masks in photographing moire specimen and master gratings. Especially important is the delineation of the grating in the areas where it cracked and flaked because of the plastic deformation of the specimen. The comparison is more suggestive if the specimen is not flat and normal to the optical axis. The depth of focus for the unmasked lens is so small that the grating will not be resolved over the whole specimen.

Figure 4c illustrates the grating frequency multiplication which can be obtained with slotted apertures even with a lens having a rather low upper frequency limit. The grating in Figure 4c is 60 lines per mm on the film, which is equivalent to 78 lines per mm (2000 LPI) on the specimen. Although this grating shows local nonuniformities, it produces very good moire fringes when superimposed with an appropriate submaster. The striations in the background of these grating photographs are traceable to irregularities in the moire master grating, the specimen surface, and the sprayed resist coating.

The gains in fringe pattern quality which result from using aperture masks are evident when fringe multiplication is carried out in the processor. There are several ways to do this multiplication.(4,5) Figure 5a was obtained by superimposing in the optical processor a specimen grating photo obtained without a mask (spatial frequency 30 lines per mm) and a submaster made by ordinary photoreduction to a spatial frequency of 58 lines per mm. The moire fringes which result from mismatch and strain are not sharp over the field. Figure 5b was derived by superimposing a specimen grating made with a slotted aperture tuned to 60 lines per mm and the same submaster used for Figure 5a. Considerable improvement is apparent; more improvement should be evident if the submaster had been made with a filter mask.

Finally, Figure 6 illustrates the degree of sensitivity multiplication obtainable with the equipment on hand. Without slotted apertures, it was impossible to produce specimen grating photos which would work in the optical processor with the rather poor submasters of about 118 lines per mm made with the same equipment. The maximum sensitivity multiplication factor obtainable was three. The specimen grating photo made with the slotted aperture at 60 lines per mm (see Figure 4) could be used in the processor with the 118 lines per mm submasters with good results. Figure 6 is a representative fringe pattern obtained with this procedure. A sensitivity multiplication factor of four (equivalent to a 157 lines per mm specimen grating) is thus obtained with a 39 lines per mm specimen grating and quite ordinary equipment. Additional multiplication could be attained if the specimen gratings could be magnified further when photographed, if the submaster grating copies had been made by photography with suitable filter masks, or the camera lens had a greater frequency response so that higher harmonics of the specimen grating could be selected and recorded.

Observation at the camera image plane shows that slotted apertures of the type described in this report can be used to obtain good grating (parallel lines) photographs from specimen arrays which are grids (orthogonal lines) or dots. The specimen, camera, or aperture mask could be rotated 90° to obtain photos of the two orthogonal grating arrays, with the added possibility of multiplied frequency, from a single specimen dot or grid pattern.

It is worth mentioning that isolation of a single harmonic of the specimen grating produces a sine grating at the photo image plane. Such a grating may create inconvenient restrictions in optical data processing, where it is often better to have a ruling which produces several diffraction orders. A workable semblance of a ruling was produced from the sine grating in the specimen photos by using fairly heavy exposures and more intense development. Such procedures can be tailored somewhat to fit particular data processing requirements; in reality, the optical data processing is quite forgiving of lack of foresight in this respect.

SECTION IV

CONCLUSIONS

1. Even with rather poor quality specimen gratings, slotted apertures may be used in a camera lens to create grating photographs having spatial frequencies which are integral multiples of the fundamental specimen grating frequency.

2. The higher frequency specimen grating photographs can be used alone or in combination with magnification and various optical data processing procedures to attain moire sensitivities which are several times higher than the sensitivity attainable with the basic specimen grating. The increases of sensitivity mentioned above are multiplicative.

3. The slotted aperture filters, whether used to multiply grating frequency or not, allow the use of a poorer photographic lens and give

improved rendering of the specimen gratings, especially in areas where the specimen grating may be damaged or of poor quality.

4. The slotted apertures give adequate resolution of the specimen grating over a greater depth of field than does an unfiltered lens, thereby making possible photography of gratings on curved or inclined specimen surfaces.

5. Slotted apertures can be used to obtain grating photographs (parallel lines) from grid (crossed lines) or dot specimen arrays.

SECTION V

ADDITIONAL POSSIBILITIES

The results of the limited experiments described above suggest additional possibilities for gaining flexibility and improved results in moire work. Three such ideas, not verified by testing are:

1. It seems logical that slotted aperture filters could be used to obtain improved fringe definition in real-time and double-exposure moire measurements where superposition of master and specimen gratings is performed at the image plane of the moire camera.

2. Two pairs of slots could be used in the aperture mask in order to obtain better rendition and/or multiplication of spatial frequencies in photographs of two-dimensional moire grid and dot patterns.

3. It should be possible to use a triagonal dot pattern for the specimen array and three separate orientations of the slotted aperture mask to obtain independent moire measurements of displacement components along three axes. This version of the moire strain rosette would give in a simple way all the data needed to establish the strain state everywhere in an arbitrary two-dimensional strain field.

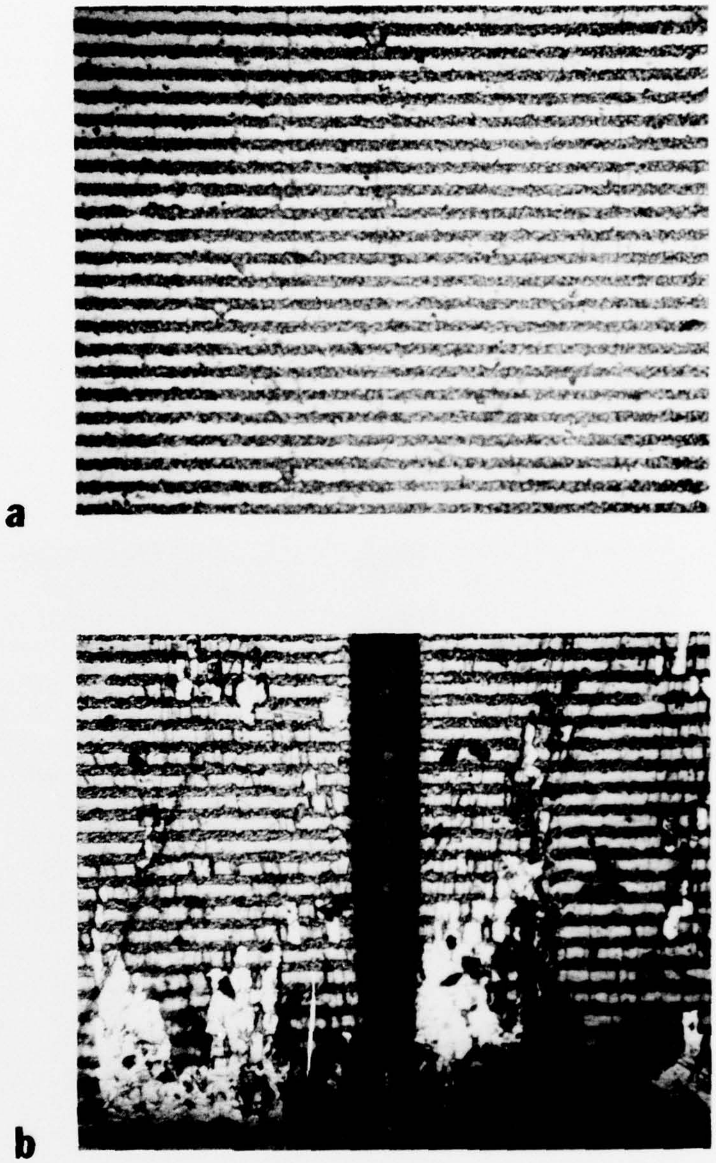

Figure 1. Photomicrographs of 39 lines/mm (1000 LPI) specimen grating in photoresist:

(a) in small strain region
(b) adjacent to hole in large strain region.

Figure 2. Photomicrograph of negative photograph of specimen grating obtained on 649-F plates at f11 with white light and no filter mask.

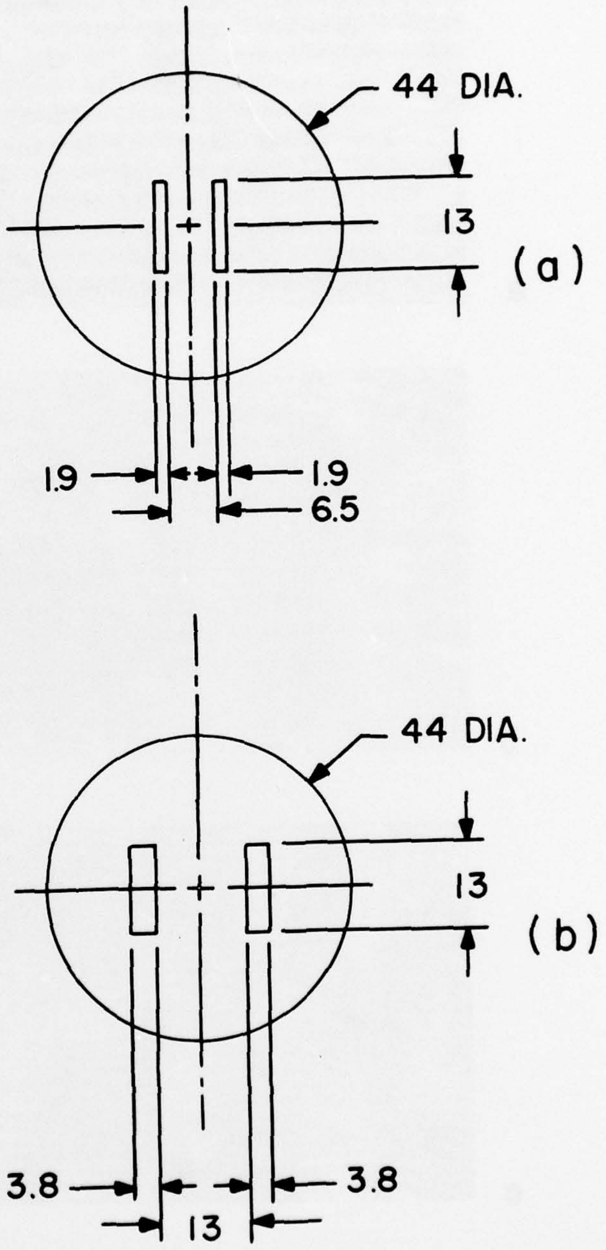

Figure 3. Slotted aperture masks used in photographing moire gratings:

(a) mask for 39 lines/mm (1000 LPI) at specimen
(b) mask for 79 lines/mm (2000 LPI) at specimen.

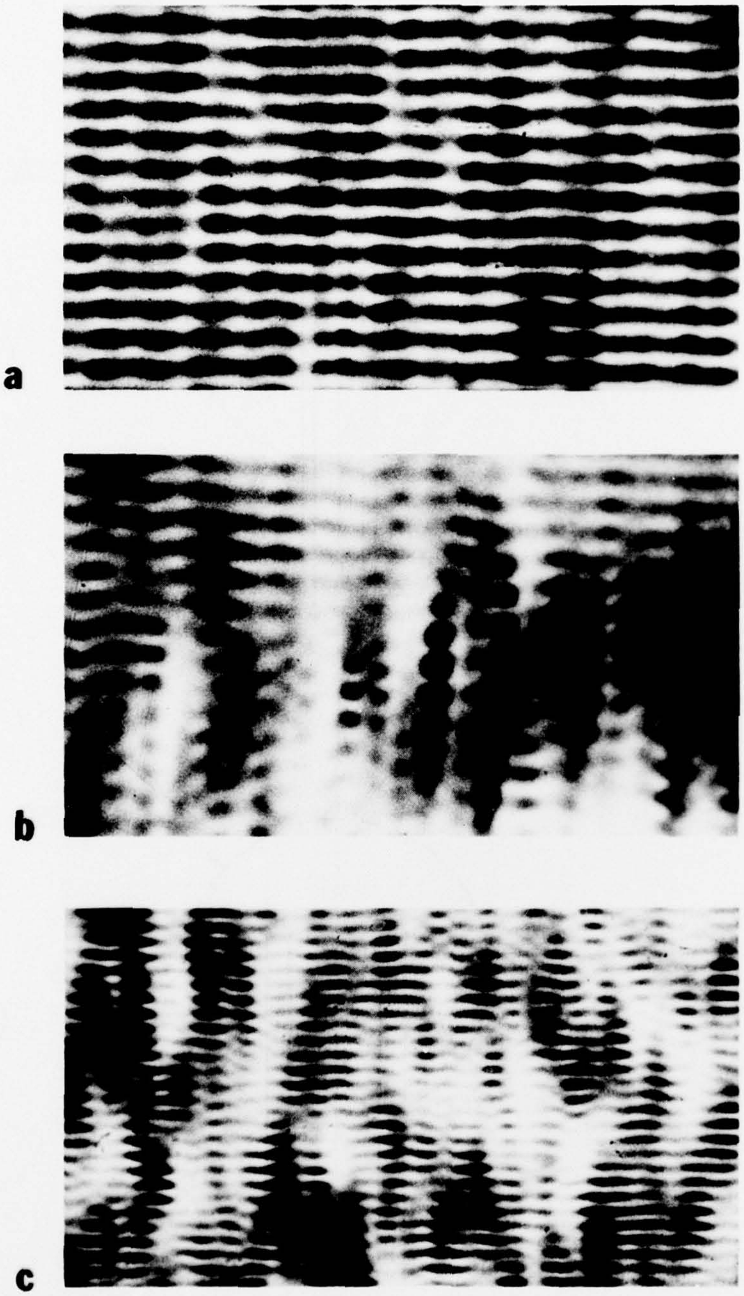

Figure 4. Photomicrographs of negative photographs of specimen grating obtained on 649-F plates with slotted aperture masks and white light.

- (a) in small strain region with aperture having 39 lines/mm (1000 LPI) center frequency at specimen
- (b) same as (a) but in large strain region near hole
- (c) in small strain region with aperture having 79 lines/mm

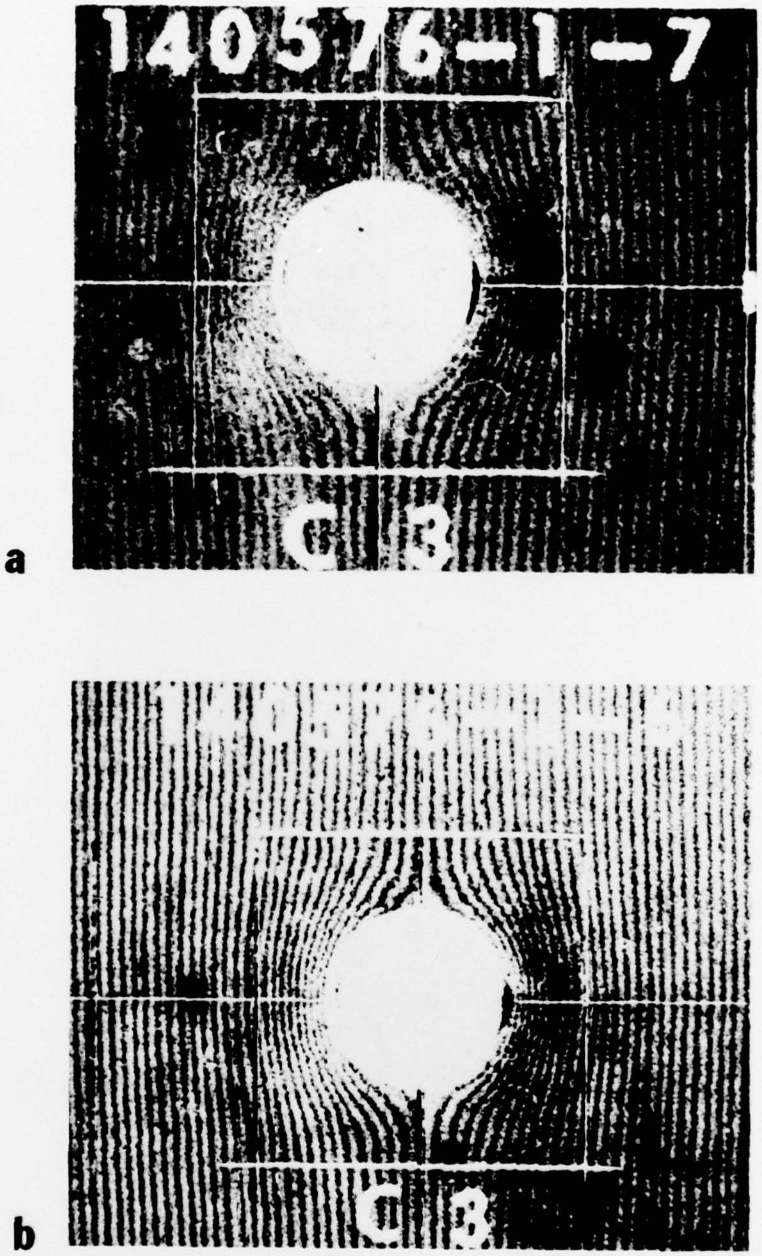

Figure 5. Improvement in multiplied moire fringe patterns obtained by using filter mask tuned to twice specimen grating frequency. Sensitivity multiplication is two.

(a) result using specimen grating photographed without slotted aperture.

(b) result using specimen grating photographed with slotted aperture tuned to 79 lines/mm (2000 LPI) in specimen plane.

Figure 6. Sensitivity multiplication of four using specimen grating photographed with slotted aperture tuned to 79 lines/mm (2000 LPI) at specimen or 60 lines/mm (1522 LPI) at photoplate superimposed in processor with submaster grating (poor quality) of 118 lines/mm (3000 LPI).

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