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EVALUATION OF MOIRE TECHNIQUES FOR WIND TUNNEL METROLOGY

Interim Report

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1. Report Period

This report covers the period from 1 April 1981 to 30 June 1981 for work conducted under research grant number NAG-1-143 from the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia.

2. Study Objectives

The purpose of this program is to investigate the development of a moire technique suitable for the analysis of object deflections in the cryogenically cooled, transonic wind tunnel at NASA, Langley Research Center. The operating environment for the new wind tunnel has a temperature range of 77 to 3,390°K (140 to 610°R), pressure to 91,390 Kgs/sq. meter (130 psia), and noise to 150 dB SPL. Expected object deflections of 75 millimeters (3 inches) need to be measured accurately to better than 1 part in 1,200. Contact methods provide only a limited number of data points at the risk of disturbing the flow or mechanically changing the response of the structure. The moire technique under investigation provides a wide range of sensitivity with a full-field, noncontact approach. The objectives of this study are: (a) to demonstrate projection moire as it would be used to study structural deflections, (b) to use optical processing to multiply the sensitivity of the moire, and (c) to investigate a system design based on the requirements of the moire technique and the restrictions imposed by the wind tunnel geometry.

3. R & D Status Report

Moire testing is a full-field, noncontact method of measuring out-of-plane displacements of a structure. There are five basic types of moire: shadow, reflection, projection, contact, and holographic. Shadow moire is clearly the simplest, requiring only that a grating be placed close to the test object which is then illuminated by a point source. The shadow of the grating on the object as viewed through the grating creates a contour moire which maps the topography of the object. Because of the sensitivity to surface topography and the requirement that a grating be placed close to the object, shadow moire is not suitable for testing in a wind tunnel and has not been pursued.

Reflection moire requires that the surface of the object be specular. A grating can be reflected off the object and imaged onto a reference grating. To accomplish this, the object must be viewed at the specular angle. Because of these restrictions, this approach is also not desirable for testing in a wind tunnel.

Projection moire provides greater versatility than shadow or reflection moire. A grating is projected onto the test object. This object grating is photographed at some angle other than the projection angle and compared to a master reference grating creating the moire. If the reference grating is made photographically, directly from the image of the object grating, the contour of the object will be subtracted out of the moire and only displacements from the reference position will be measured. Projection moire is a possible candidate for wind tunnel testing if the physical facilities permit two suitable access angles.

Contact moire uses a grating applied directly to the object. The grating can then be photographed directly and compared to a reference master grating, which can be a photograph of the object grating before it is deflected (thus subtracting out the object topography). Only one access angle is required for this type of moire. As an alternate approach, a second grating can be projected onto the contacted grating which will create a moire directly on the object. To subtract out the object topography, this second grating would need to be made from a photograph of the underformed contacted object grating. Contact moire would be the most appropriate approach to wind tunnel testing, if only one access angle is available.

Holographic moire involves making a real-time or double-pulsed hologram of the test object and comparing the high-frequency holographic fringes with a reference grating or another set of holographic fringes (such as in sandwich holography). Because of the stability requirements of holography and the difficulty of interpreting the data, holographic moire is not seen as a viable option for wind tunnel testing.

The above moire techniques are summarized in Table 1. The systems being investigated are projection moire, contact moire, and possible combinations of the projection and contact moire. An appropriate system will be relatively insensitive to vibrations of the system and capable of taking data quickly, probably using a short pulse light source. A real-time visualization would be possible, but to obtain high sensitivity in areas of interest, optical processing will be required.

4. Results

As a demonstration of testing dynamic objects with projection moire, we have applied the technique to a ten-inch vibrating steel plate driven at resonance. The object grating was produced by imaging a ronchi ruling onto the plate so as to have approximately a 2-line-per-millimeter (50-line-per-inch) grating on the object. The grating was photographed at various points in the vibration cycle, using a Q-switched ruby laser to freeze the motion of the plate. By taking two of the photographs 180 degrees apart in phase as referenced to the vibration cycle of the plate and laying one over the other, we obtained the moire pattern shown in Figure 1a. The sensitivity of this moire is approximately 500 microns (0.02 inches) per moire fringe.

We then multiplied the sensitivity of this moire by optical processing to obtain a sensitivity of 250 microns (0.01 inches) and 125 microns (0.005 inches) per fringe as shown in Figures 1b and 1c. The original photographs made with the ruby laser were recopied using a high contrast process to obtain higher diffraction efficiency. The multiplication of sensitivity is accomplished by selecting out specific diffracted orders in the optical Fourier transform of the object photograph which correspond to the spatial frequency sensitivity desired. The moire is created between a master grating made in the optical processor using one of the object photographs and the image created in the optical processor of the other photograph. The direction of a deflection can be determined in the optical processor by laterally translating the master grating relative to the image of the test grating.

As an alternate approach, we made a double exposure photograph of the plate undergoing random vibrations using the ruby laser as the light source. A section of the double-exposure photograph is shown in Figure 2a. The moire created in this fashion is an additive moire which is inherently low contrast. By optically filtering out the frequency information relating to the grating and leaving only the information relating to the moire pattern, the moire pattern is effectively enhanced as shown in Figure 2b. This approach permits changes on a short-time scale to be recorded.

A technique similar to double-exposure moire is time-average moire. To demonstrate time-average moire, we projected a reference grating onto a ten-inch steel plate which had an object grating glued onto its surface (using stripping film). The period of the contacted object grating was 4 lines per millimeter (100 lines per inch). The projected grating was made using an Argon laser and a Wollaston prism. By mismatching the period of the projected grating relative to the object grating, we created a set of bias fringes with a period of 1 line per millimeter (25 lines per inch). The low-frequency bias fringe was easy to record, since it did not require high-resolution optics, yet the sensitivity was still determined by the projected grating which was 5 lines per millimeter (125 lines per inch).

When the plate was driven at resonance, we obtained the low-contrast, time-average moire shown in Figure 3a. This photograph is similar to the double-exposure photograph made with the ruby laser. By optically filtering the time average photograph we obtained the moire pattern shown in Figure 3b. Time-average moire would allow oscillatory motions to be integrated over a time period and recorded using very little light.

An important technical consideration for any of these moire approaches is the type of photographic film required. The photographic film should be high contrast and fast, with sufficient resolution for the type of moire. We conducted a survey of some possible films. The results are summarized in Table 2. Photomicrographs of a sinusoidal grating photographed with the various films are shown in Figure 4.

Holographic film (Figure 4d) gives very high resolution, high contrast, and relatively low noise. The only real limitation of the holographic film is the relatively slow speed. Technical Pan film (Figure 4c) was found to give a reasonable trade-off between speed and resolution. At the ruby laser wavelength the Technical Pan film was found to have the highest sensitivity. Both the holographic plate copy and the lithographic film copy of the Technical Pan film (Figure 4e and 4f) showed higher contrast, thus higher diffraction efficiency, and less noise. The holographic plate had the advantage of being on a glass plate which introduced less scatter than the film base of the lithographic film.

5. Future Work

The demonstrated sensitivity of the pulsed moired to date has been 125 microns (0.005 inches) per fringe, which would yield a readable sensitivity of about 25 microns (0.001 inches) of deflection. We will be further investigating the pulsed and contact moire. These approaches can be scaled up to larger objects using a lower frequency grating on the object. We will also be investigating additional possible films.

The results of this investigation will depend on the physical limitations imposed by the wind tunnel and test objects on the particular moire systems. Based upon this investigation, we will identify what would be required to develop an appropriate moire system for wind tunnel tests.

6. Overall Program Status

The present level of effort is expected to meet the program objectives as stated.

6.1 Performance and Cost Report

Funds spent to date	$10,318.61
Outstanding Commitments	740.00
Percentage of total grant amount spent to date (funds spent + outstanding commitments/$29,374)	38%
Remainder of grant funds	$18,315.39

6.2 Overall Cost Status

The remaining funds are sufficient to complete the program.

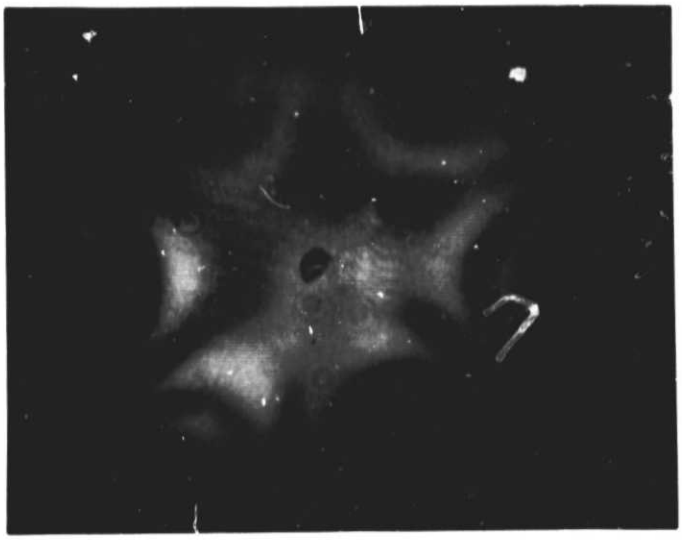
TABLE 1. COMPARISON OF MOIRE TECHNIQUES

Technique	Advantages	Disadvantages	Comments
1. Shadow Moire	Simple	Limited sensitivity Requires reference	Object and reference grating need to be in focus simultaneously
2. Reflection Moire	Simple, light efficient	Object must be specular viewed at specular angle	
3. Projection Moire	Versatile, not contour sensitive, real time	Requires high resolution optics	Time average moire possible with optical processing
4. Double Exposure Optically Processed Moire	Freezes motion when pulsed source is used, optical multi-plication possible	Not real time, film limitations, only practical with pulsed source	A very bright pulsed source may be re-quired though it need not be a laser
5. Contact Moire	Resolution not limited by optics, can yield in plane deformation	Requires grating on object, geometry sensitive, must be viewed off axis or have second projected grating	Can yield high resolution when coupled with optical processing
6. Holographic Moire	High sensitivity, no high resolution optics	Requires high stability, difficult to control sensitivity	

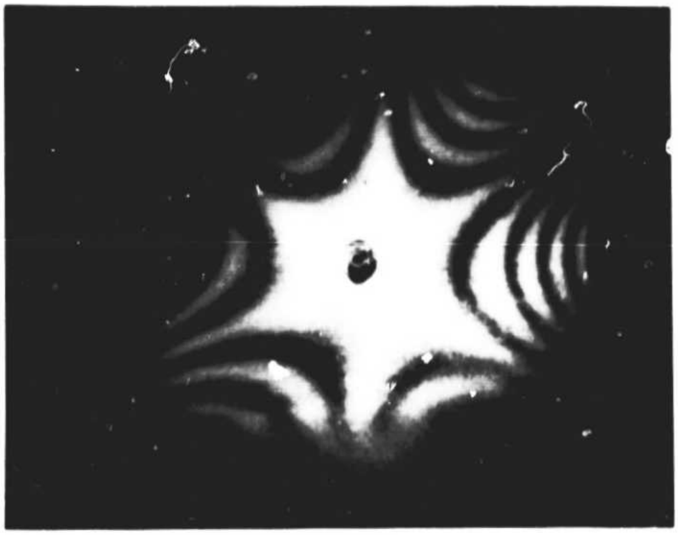
TABLE 2. COMPARISON OF POSSIBLE FILMS FOR MOIRE PHOTOGRAPHS

Film	Exposure	Devel.	Comments
1. 35 mm Litho-graphic film	9 sec	Litho, 2 min	High contrast, noisy, (no ruby sens).
2. Polaroid Pos/Neg	-	50 sec	Low contrast, grainy
3. Litho Copy of Polaroid Pos./ Neg	-	-	High contrast, sensitive to irregular orig.
4. Agfa Gaveart 10 E56 Holographic Plate	1 sec	HRP, 10 min	High contrast, very fine grain
5. Technical Pan	1 sec	D-19, 6 min	Med. contrast, med. grain
6. Agfa Gaveart 10E75 copy of Technical Pan	4 sec	HRP, 8 min	High contrast, some noise from Tech. Pan base
7. Litho copy of Technical Pan	0.4 sec	Litho, 6 min	High contrast, Noise from base
8. Panatomic-X	2 sec	D-19, 4 min	Low contrast, grainy

LIST OF FIGURES



(a) 1X Multiplication



(b) 2X Multiplication

(c) 4X Multiplication

Figure 1. Steel Plate Resonating at 60 Hz, Various Sensitivities.

Figure 2a. Double Exposure of Vibrating Steel Plate.

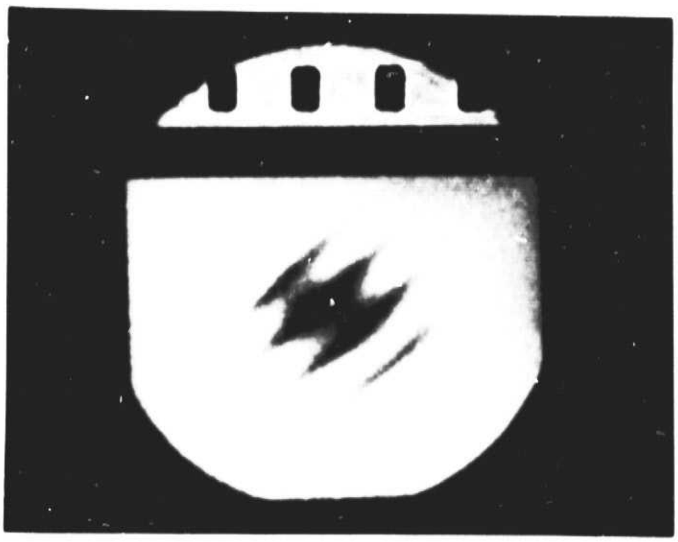


Figure 2b. Double Exposure After Optical Filtering.

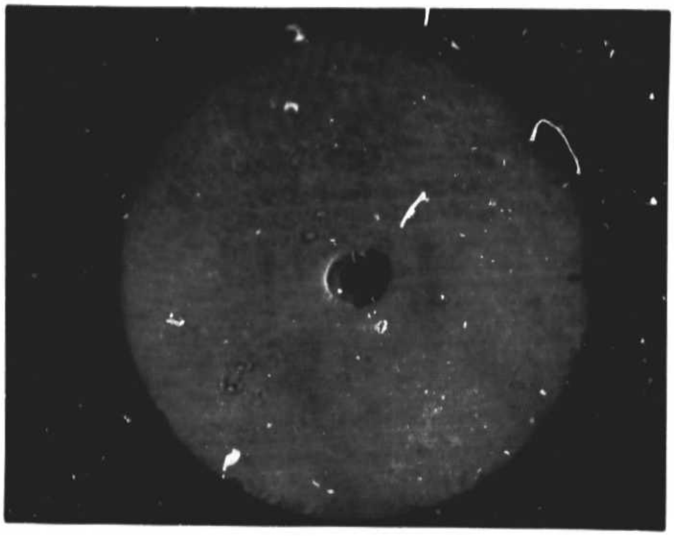


Figure 3a. Time Average Moire Photograph of Resonant Plate.

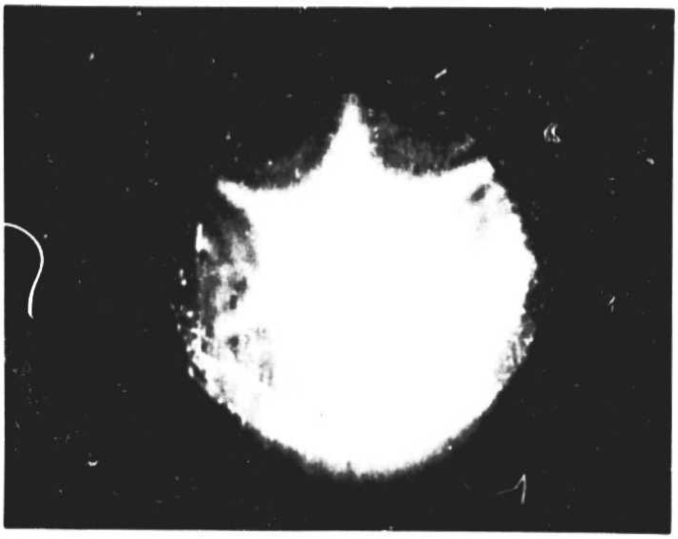


Figure 3b. Time Average Moire After Optical Filtering.

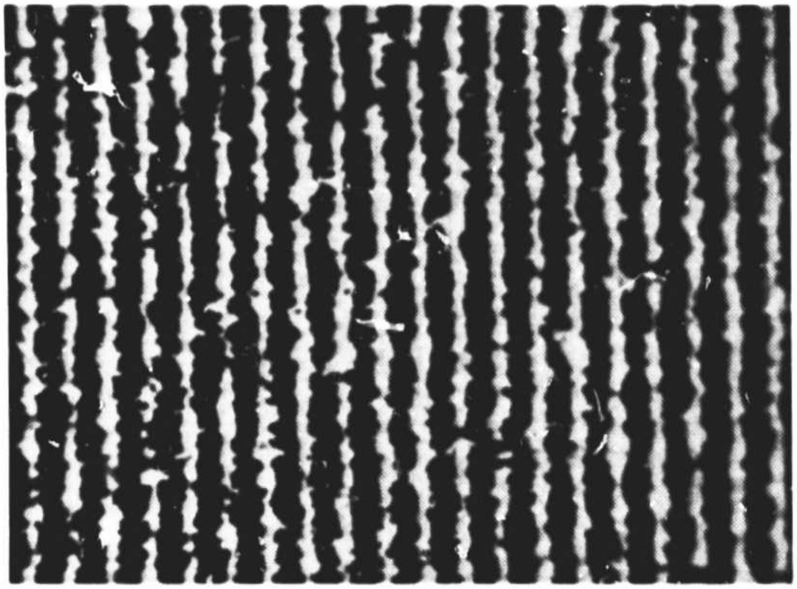


Figure 4a. 35 mm Lithographic Film Photo of Grating.

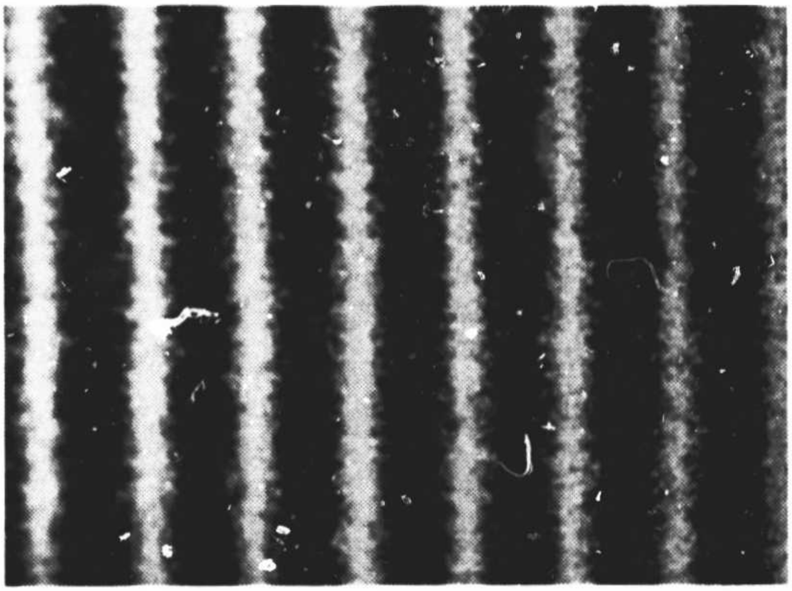


Figure 4b. Polaroid Pos/Neg of Grating.

Figure 4c. Lithographic Copy of Polaroid Pos/Neg Photo.

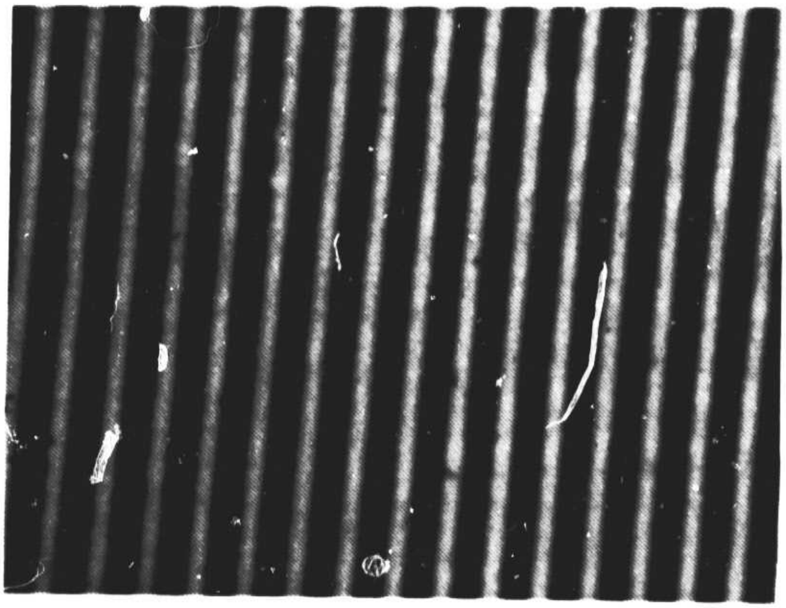


Figure 4d. Holographic Plate (10E56) Photo of Grating.

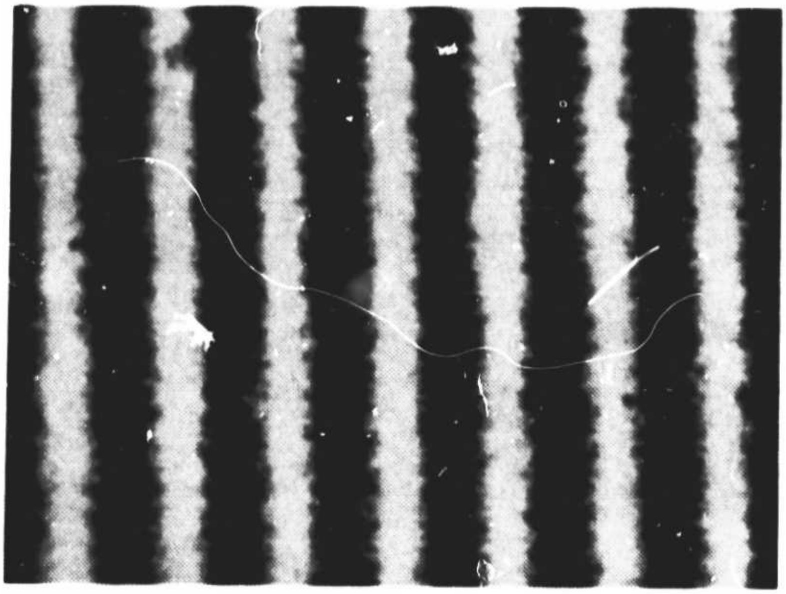


Figure 4e. Technical Pan Film Photo of Grating.

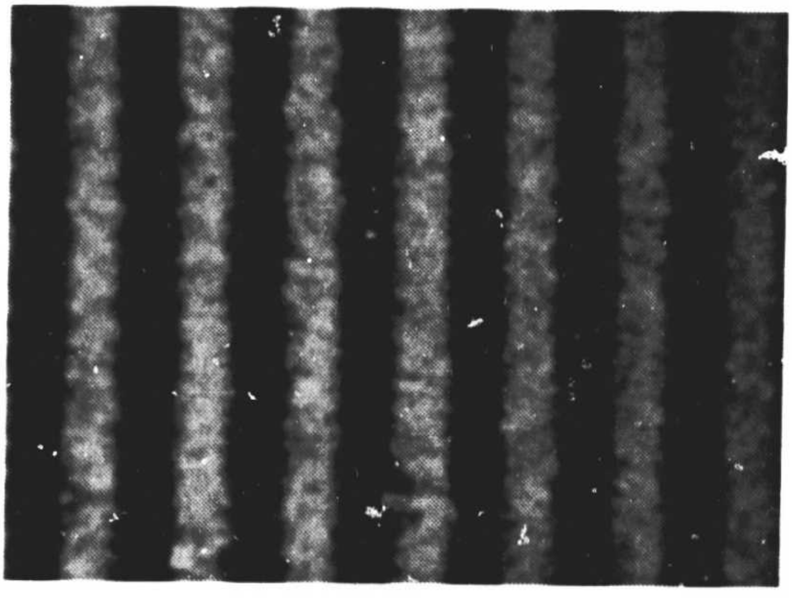


Figure 4f. Holographic Plate (10E75) Copy of Technical Pan Photo.

Figure 4g. Lithographic Copy of Technical Pan Photo.

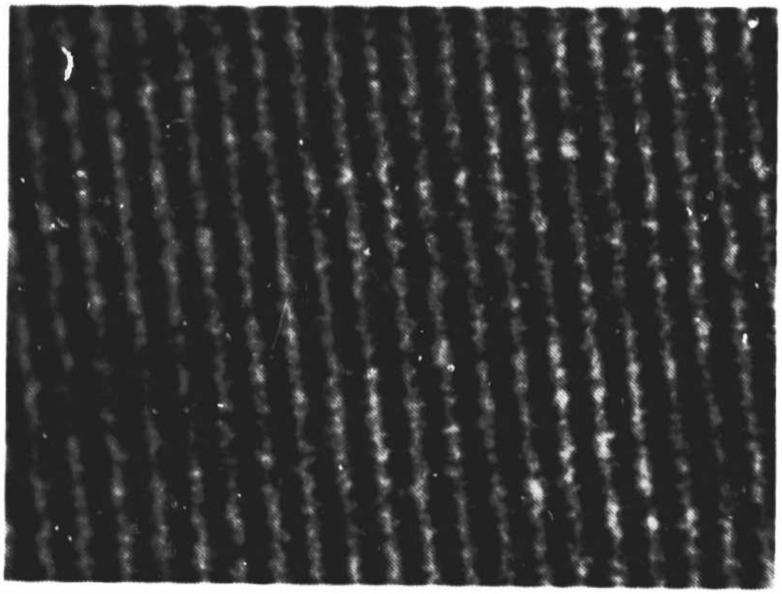


Figure 4h. Panatomic-X Film Photo of Grating.