Compact 3D Profilometer with Grazing Incidence Diffraction Optics

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Abstract

A new type of diffraction range finder is disclosed that places the primary grating at an angle of grazing incidence relative to the receiver. The new design offers improvements over earlier prototypes in reduced package size, reduced chirp depth and a highly anamorphic behavior that provides a high profile to depth ratio. Demonstrations with transmission and reflection types of diffraction grating corroborate predictions.

1. Prior Art

Diffraction range finders work on the principle that higher-order diffraction images are displaced from the central zero-order as a function of target distance. In these devices, the distance of the lens to grating on the receiver side is related to the distance of a target to grating on the transmitter side, and the greater the open air interior space inside the receiver, the greater the working distance of the range finder. This is somewhat similar to telescopic lenses of long focal length where the primary optic is positioned away from the focal plane in order to achieve magnification of distant targets.

Our 1997 demonstration of a hand held range finder based on diffraction optics earned a NASA-juried prize for Small Business Innovative Research [1], and the demonstrated RMS repeatability error of less than 300 microns over 300 mm using a video grade CCD. This was a promising performance benchmark [2], but our prototype hand held profilometer (named “Moly” for its molybdenum disulfide impregnated nylon shell) had a drawback not contemplated in the original design objective – significant interior open space. Moly was not the miniature “3D paintbrush” we had contemplated.

2. Grazing Incidence Configuration

Unlike common refractive or reflective optics, many diffractive primary elements can alter the ray path at an *evanescent angle*, that is to say, injecting the wave front directly into the optic substrate itself. *Grazing incidence*, the angle of diffraction just shy evanescence by a few degrees, similarly can be achieved. This unique capability of diffraction gratings to collect light parallel to or nearly parallel to the grating plane can be exploited in a diffraction range finder to reduce the interior volume of the device. One authority characterizes the ramifications this way:

> Various types of holograms have been developed during the past half century. While transmission and reflection type holograms have enjoyed increasing popularity over the years, increasing attention is being given to grazing incidence (e.g., "edge-illuminatable" or "edge-referenced") type holograms. Grazing incidence as used herein will refer to a large, or "steep" angle of incidence with respect to the normal to an interface between two surfaces. The primary reason for the increasing interest in grazing incidence holograms is due to its compact geometry that lends itself to convenient use in diverse applications. [3]

Unfortunately, grazing incidence was not an option with our first prototype. Moly’s grating was a hologram made by the venerable Leith-Upatniek method using a silver halide-depleted emulsion. This is to say that a silver halide holographic plate was placed at the intersection of a spherical wave front and a plane wave front which were off-axis relative to each other. There are restrictions on the allowable placements of the object and reference beams in silver halide holography, and to our knowledge, grazing incidence is not practiced during exposure in air. [4] Furthermore, since the silver halide-depleted grating made by this method is essentially a volume structure, efficiency in playback is dramatically reduced for any off-axis reconstruction. It is true that the theoretical angle of diffraction in any hologram can be adjusted down to grazing incidence in playback, albeit not in exposure, but grazing incidence produces such low efficiency in thick silver halide emulsions that none of our holograms performed at grazing incidence. So with Moly we went for “the broad side of the barn”. Our goal in specification of Moly’s holographic grating was to realize a working reduction-to-practice, and we are satisfied that we demonstrated conclusively that a machine vision 3D image can be recorded by taking the higher-order diffraction image as it shifts relative to the central zero-order as a function of target range.

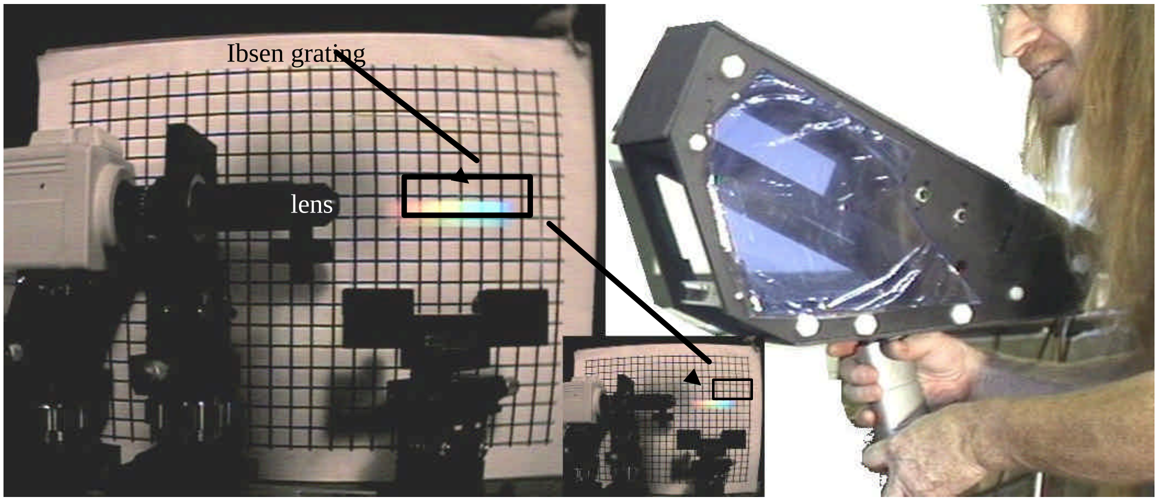

Figure 1 Comparison of package for Moly on the right with grazing incidence on the left. The grid is in cm. The middle insert shows grazing incidence package to same scale as the photo of Moly.

2.1 Surface Relief Diffraction Gratings

A follow-on goal after Moly was to demonstrate a diffraction range finder with reduced package size. In order to achieve this, we needed a grating that would work in grazing incidence. The most common type of diffraction grating for grazing incidence are surface relief gratings. One type is the echelon grating made originally by Michelson through the superimposition of thin glass plates. Today variants of gratings of this type, echelles, are made from a single substrate and find extensive use in astronomical spectroscopy, but these very expensive specialty items were neither available to us for experimentation nor does their use of very high diffraction orders correspond with our general approach of using the first-order of a high frequency grating to form a range image.

Fortunately, exotic gratings are not required to achieve grazing incidence as we conceive it. Garden variety surface relief gratings produce discernible grazing incidence images. The effect can be seen in any compact disc or DVD using the naked eye. Simply observe a point of illumination perpendicular to the disc plane from a view almost grazing the edge of the disc. A chromatic dispersion will be visible. In scientific optics, a grazing incidence configuration called a Littman-Metcalf cavity is central to recent innovations in frequency-tuned diode lasers. [5] A laser beam is injected onto the surface of a grating at grazing incidence. Its considerable width causes the narrow beam to be redistributed into a sheet of light that strikes a mirror parallel to the grating surface. The resulting standing wave can be tuned by a slight rotation of the grating-mirror assembly. CD's, DVD's and the gratings used in the Littman-Metcalf cavity are surface relief gratings that produce reasonable efficiencies at grazing incidence in an air interface.

We obtained a sample surface relief phase mask transmission chirp grating with straight rules courtesy of Ibsen Micro Structures A/S.[6] This sample grating was originally intended for use as a master in the production of Bragg gratings in fiber optics. It is optimized for light at UV frequencies where the grating has high zero-order suppression. To achieve the suppression, it has a groove depth of approximately 220-250 nm. The Ibsen grating has a center period of 1067 nm with a linear chirp of 6.8 nm/cm over its length of 5 cm. It is 1 cm in height and sits on a 75 x 75 mm glass substrate. In the application for which it was actually intended, the grating is illuminated by a collimated UV laser light source perpendicular to the grating plane, and the +/-first-order images constructively interfere within the fiber optic to form a Bragg grating inside a doped glass fiber. [7] The 5:1 aspect ratio of the Ibsen grating is attributable to its use in the exposure of long and narrow fibers, but it conforms to our requirements for a grazing incidence configuration where aspect ratios are skewed by the shallow angle of view.

Compared to Moly's large 100 x 125 mm grating, the Ibsen chirp grating (10 x 50 mm) was in and of itself a considerable reduction in package size, but the most significant size reduction was in the placement of the camera. Instead of Moly's camera-to-grating stand-off of 450 mm which further required use of a folding mirror, a grazing incidence configuration placed the camera lens 30 mm from the near side of the grating. Figure 1 compares the relative dimensions of Moly and our grazing incidence experiment.

2.2 Some Grating Ruling Considerations

Not only does a grazing incidence configuration compress the placement of the camera relative to the grating, but additionally the extremely shallow camera angle relative to the grating plane results in a marked non-linearity in the effective variation of pitch across the face of the grating as received at the focal plane. We illustrate this in Figure 2 by comparing two camera configurations, one facing the grating normal and the other in grazing configuration. Note how the chirp as received at the focal plane varies. The former is linear and the latter is exponential, notwithstanding that in this calculation, the grating itself had a linear variation in pitch.

Moly's grating has a 100 nm chirp from 550 to 450 nm over a length of 100 mm. The Ibsen grating has a much shallower chirp of 30 nm from 1080 to 1030 nm over 50 mm. Yet both produce collimated ray structures.

A comparison between the ray structures generated by the Ibsen grating in grazing incidence versus a grating normal configuration is very telling with regard to the change in performance induced by the grazing incidence configuration. As shown in Figure 3, the collimated ray structure induced by grazing incidence permits operation of the range finder at long stand-off to target. Therefore, we have invented a new kind of telescope with a diffraction grating primary [*] rather than the common refractive or reflective primaries used in conventional telescopes.

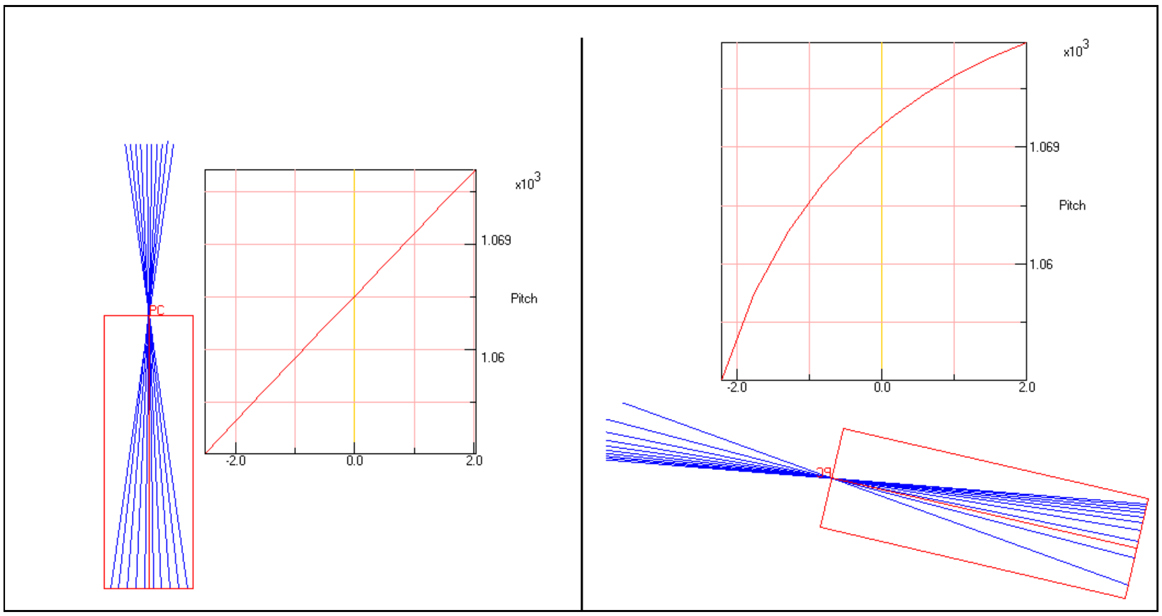

Figure 2 A comparison of normal incidence configuration from grating to camera illustrated on the left with grazing incidence configuration from grating to camera diagrammed on the right. Grazing incidence results in a non-linear spread of pitch from what was a linear grating. In the associated graphs, pitch units are in nm; focal plane in mm

The significance of the exponential change in perceived grating pitch at the focal plane in a grazing incidence device can appreciated by studying the intrinsic benefit of a hyperbolic frequency chirp in the grating as is demonstrated in our prototype, Moly. In this design an attempt was made to linearize the relationship of target distance to displacement of the diffraction image across the focal plane. In any conventional triangulation range finder or any diffraction range finder made with plane gratings, perspective foreshortening results in an inverse square loss of resolution due to perspective foreshortening. We compensate for this foreshortening by raising the frequency of the grating as the square of the target distance. However, for a significant correction, we need a considerable chirp.

A final distinction between Moly's holographic grating and the Ibsen grating used in our grazing incidence configuration is related to the geometry of the rules. In a classic Leith-Upatnieks hologram, i.e., the hologram of a single point source, rules are curved in the shape of a conical section. This benefits Moly which uses a collimated sheet of light as its source of structured illumination. As a result of the chirp in both dimensions of Moly's holographic

[*] In a telescope of this design a diffractive primary is sighted by a conventional telescope placed in a grazing incidence configuration. The design can have applications in astronomical spectroscopy. This project has been dubbed the Dittoscope.

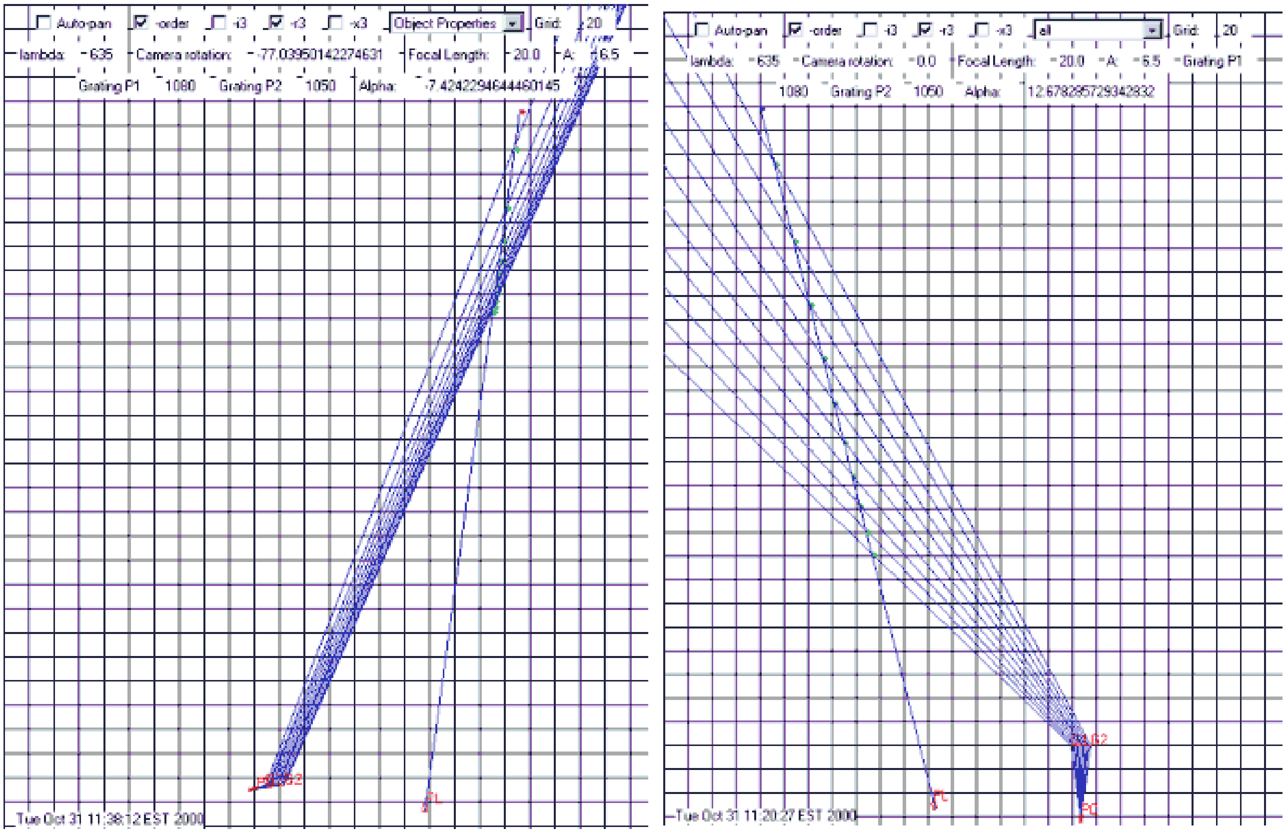

Figure Three Comparison of ray structures of grazing incidence on left with normal incidence on right. In this diffraction range finder, a structured illumination beam crosses the ray path. Their intersection of beam and rays forms a 3D profile.

grating, the acquisition region is nearly a perfectly linearized rectangle. The field-of-view of the range finder matches the rectilinear field of illumination. This fulfills a stated design objective.

In the Ibsen surface relief grating, the rules are essentially straight. One consequence is that the field-of-view of the range finder is determined in the profile dimension by the focal length of the camera and the range dimension by the leverage induced by the grating. In other words, the acquisition window is anamorphic as illustrated in Figure 4.

To those familiar with designing profilometers, the benefit of an anamorphic distortion is that the profile length can be increased without sacrificing range resolution. Conventionally this is done by using cylindrical lenses where typical ratios of height to width are at best 2:1.

The benefits of grazing incidence configurations for a diffraction range finder can now be seen to include a reduction in the size of the instrument, the reduction in the depth of the frequency chirp of the grating to produce a telecentric effect by collimating the incoming rays, and an easily controlled and powerful anamorphism that results in high “y to z” or profile line to depth ratios.

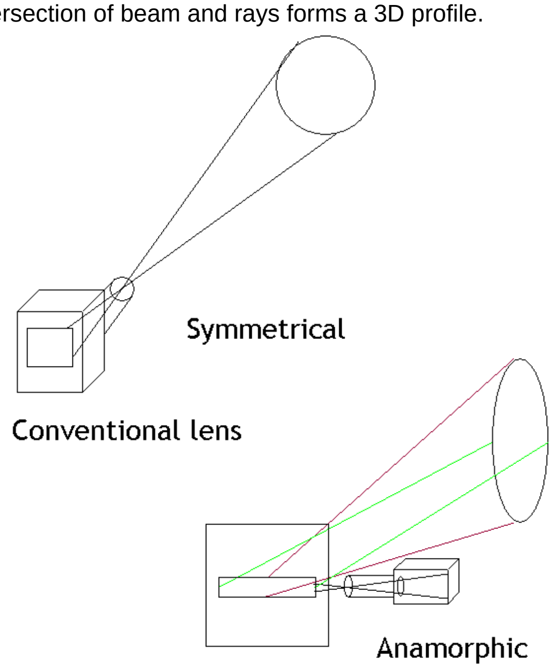

Figure 4 Applying diffraction leverage to a single axis results in a marked anamorphism in the grazing incidence configuration as compared with a conventional lens alone.

3. Experiment with the Ibsen Telecom Grating

Our initial experimentation was conducted by pushing all components to the *extrema* of our optical bench, a distance of five feet. We can compare the range image that would have been acquired by a triangulation camera at the same occlusion liability angle with the diffraction range finder simply by replacing the grating with a mirror.

There are notable distinctions between the zero-order and first-order diffraction images in Figure 5. On the one hand, the diffraction images show a bowing effect, and the poor efficiency of the sample grating restricted the length of the line of illumination. There are also artifacts of ambient illumination in the diffraction images resultant from the lack of a band pass filter in the camera for our laser line color frequency. On the other hand, the 45 degree wedge block is

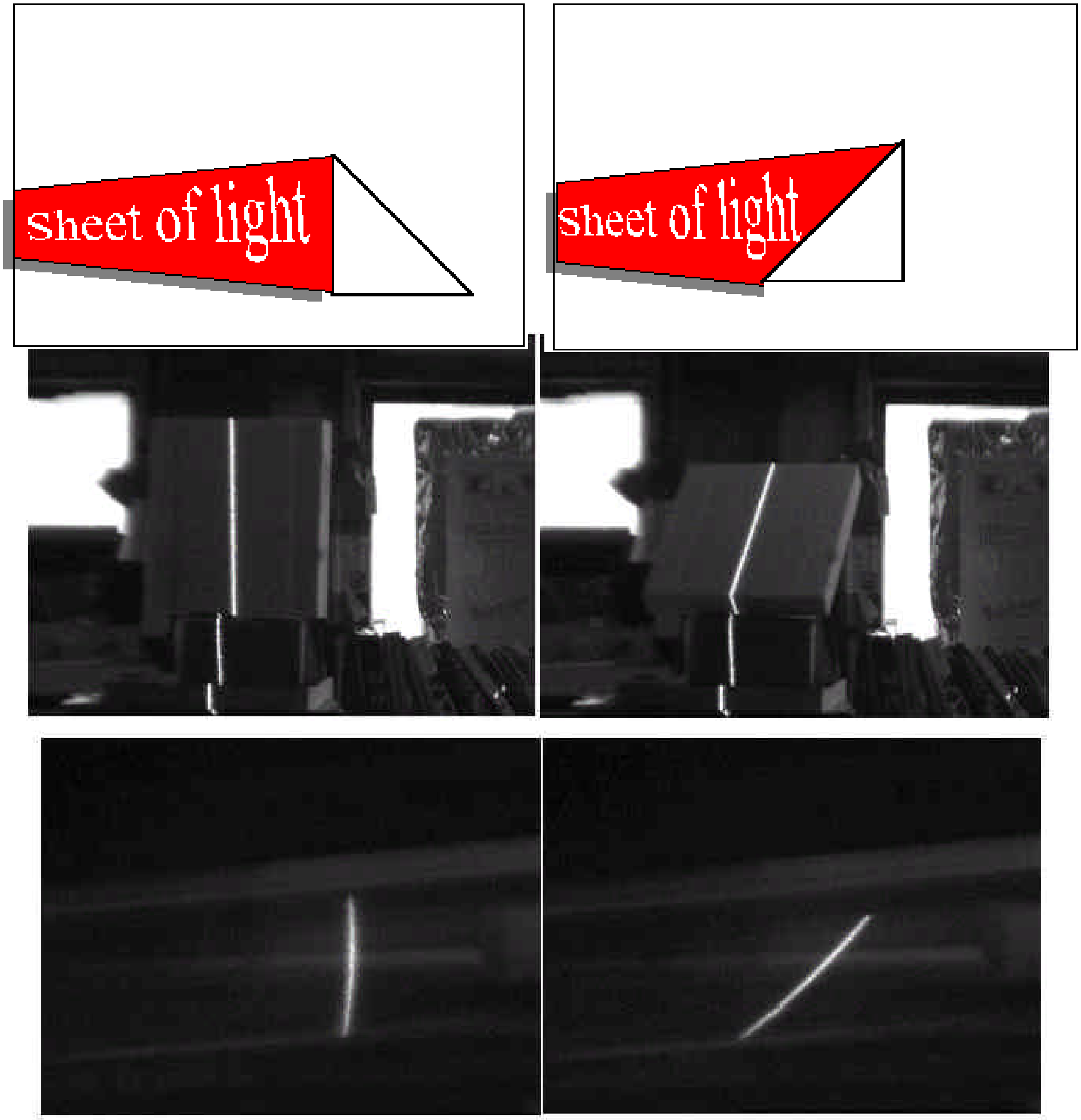

Figure 5 A sheet of light illuminates test blocks. We compare the zero-order image above with the diffraction image below.

reproduced 1:1, height to depth in the diffraction image. The zero-order image of the wedge in Figure 5 has a compressed profile.

The latter distinction is exhibited more dramatically in the profile of a mannequin head, Figure 6. The zero-order profile is seen here with the rest of the head in view. This profile (in negative) is then positioned to the right side of the sequence of profiles below in Figure 7. The other profiles were made through the grating in grazing incidence. The changes in both position and magnification were achieved simultaneously by rotating the grating. Beyond the 1:1 reproduction comparable to the test wedge in Figure 5, the magnification reaches 2:1 in the image on the left, and this magnification is a full six times the profile proportions of the zero-order image. Background noise is the consequence of using a UV-efficient grating in the red energy of the diode laser, although laser lines themselves do produce speckle.

The Ibsen grating is a transmission type. Not only is its efficiency compromised by the shallow depth of the grooves, but when compared to reflection gratings, the rules must be at least twice as deep for an equivalent efficiency. This suggests that reflection gratings would be preferable.

Figure 6 Biff, the mannequin, as a zero-order image above and to the left extreme. The diffraction profiles are shown in various degrees of magnification from a single set-up.

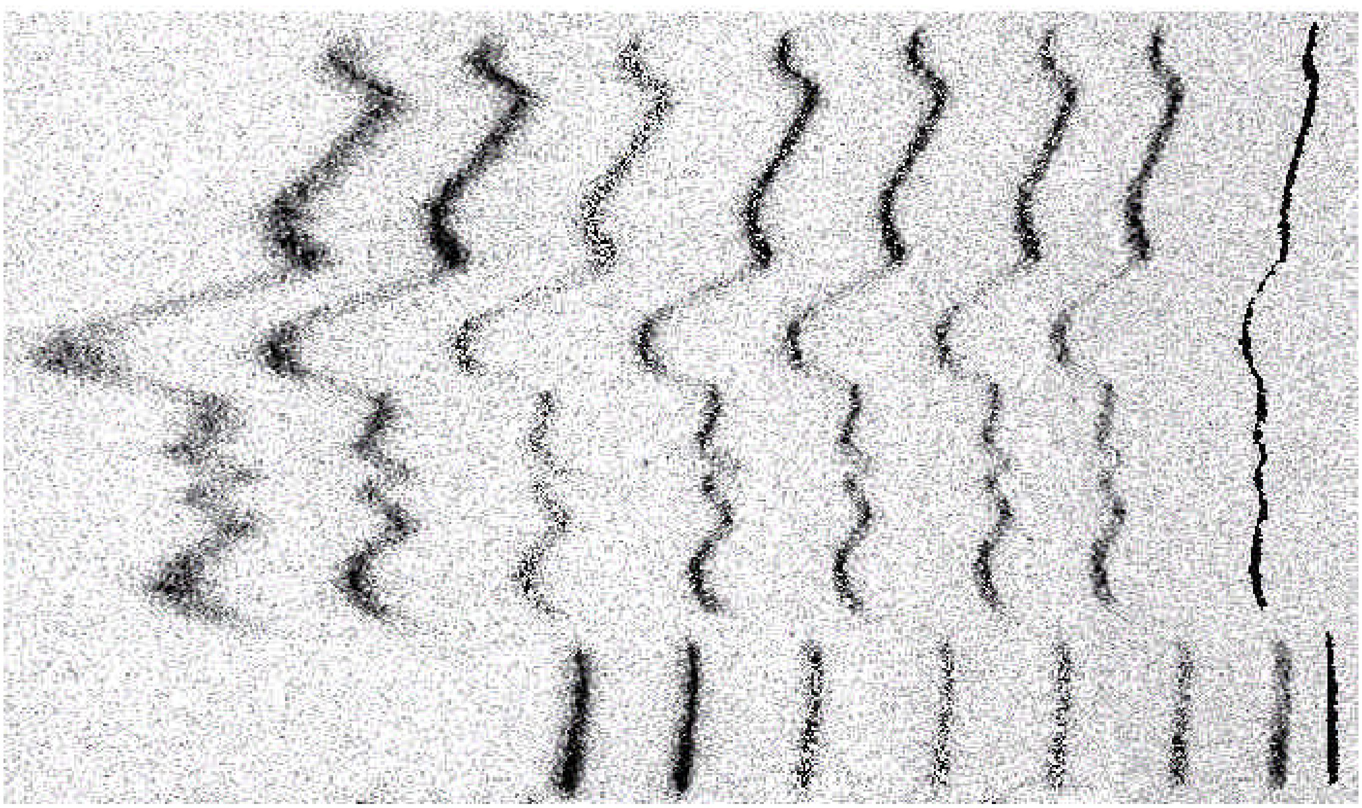

Figure 7 Biff's diffraction profile shown in various degress of magnification. All images were acquired in a single set-up, and magnification was controlled by rotation of the grating.

4 A Profilometer made with a Compact Disc

Grating materials are far more common today than in past history. The Ibsen grating is of a type widely used in the fabrication of fiber optics for telecommunication. Unfortunately, these etched glass optics which have special features for zero-order suppression in the UV are very expensive. However, there are billions of rather high quality gratings available at virtually no cost for experimentation, compact discs (CD's) and digital video discs (DVD's). These gratings are of the reflective type and have good efficiency within visible spectra. Because they are surface relief types, they also work in grazing incidence mode.

The grating pitch of CD's are standardized, although there are variations depending on record lengths in CD's and some surface feature distinctions between competing DVD types. As a general rule, CD's have a pitch of 1.6 microns and DVD's have a pitch of 0.74 microns.

4.1 Curved rules

Pitch spacing in the CD type of grating is fixed, but the rules are circular. The curvature in the rules affects the power of the grating in a manner that is similar to the chirped frequency in a variable pitch grating.

Consider the effective grating pitch along the y axis in Figure 8. The radius from the center of the co-axial circles to an intersection with y forms the hypotenuse of a right triangle and allows us to use simple Pythagorean geometry to make a calculation of the effective pitch of the grating along the y axis a distance x. Obviously,

(1) $$r = \sqrt{x^2 + y^2}$$

For any given value of x, the effective pitch p_y along the positive y axis can by known by incrementing r in steps equal to the circular grating pitch p_c.

(2) $$y = \pm\sqrt{\left(x + \sum_{n=1}^{i} p_c\right)^2 - x^2}$$

Using (2) we can simulate the effective grating pitch along the y axis of circular grating of fixed pitch. Sample calculations are seen in Figure 8. To those practiced in the art, the change in pitch along the y axis will immediately be seen as a variable pitch or chirp grating which can be expected to have a similar effect as a variable pitch grating. The depth of the chirp varies as a function of the distance from the focus of the curved rules.

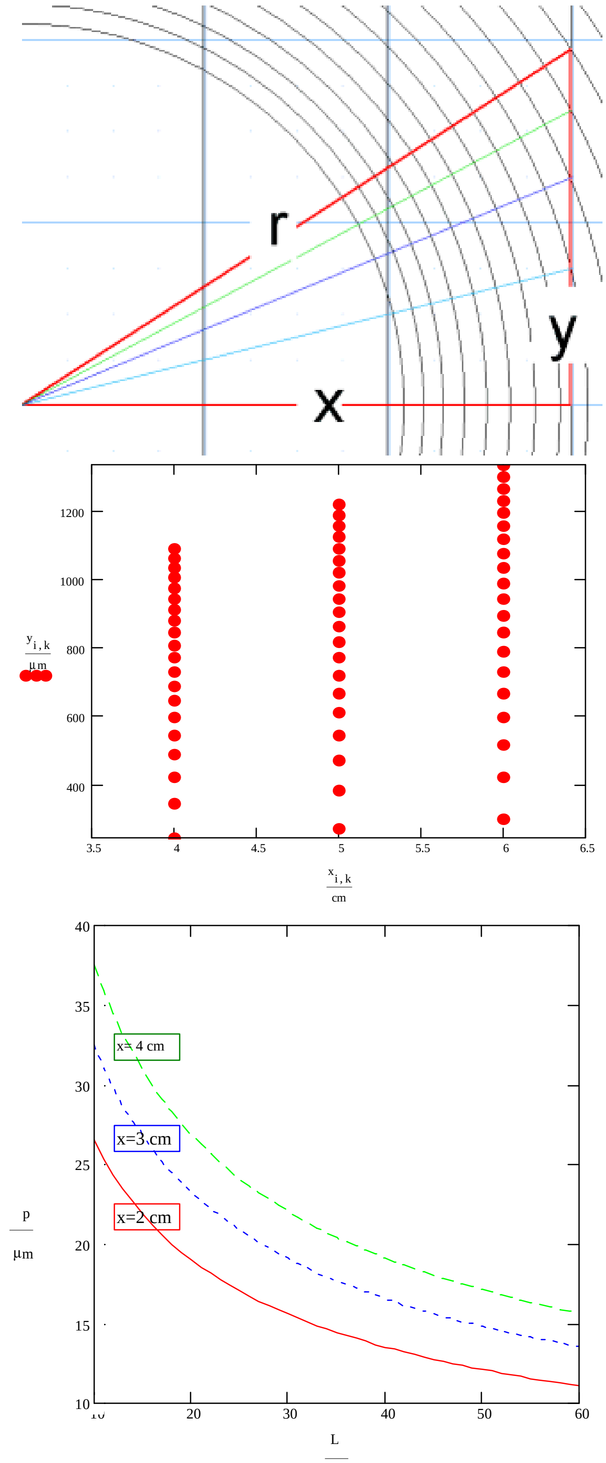

Figure 8 Virtual chirp introduced by rule curvature in a DVD We calculate the frequency by the Pythagorian method. The depth of chirp can be visualized using two graphs, one showing relative displacement of the grooves in the y axis and the other showing pitch vs. vertical position for three lines orthogonal to the x axis.

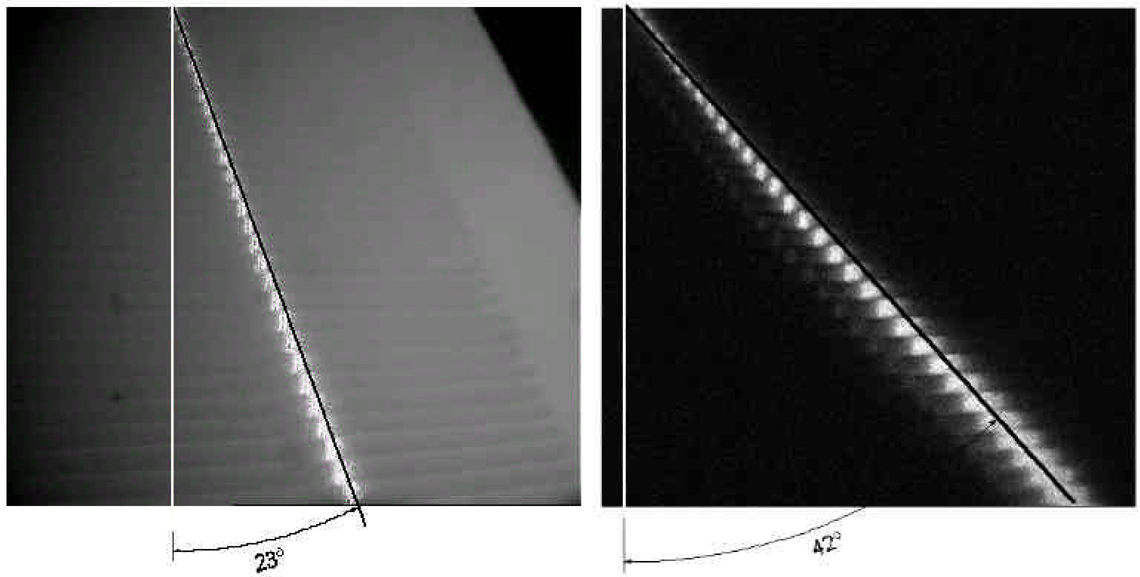

Figure 9 Experiment with a CD as an optical element in a diffraction profilometer. Comparison on zero-order image on left with first-order image on right.

4.2 Experiment with Compact Disc

Using the same test block as in the prior experiment with the Ibsen grating (see Figure 5) but placing the target in the near-field at a 27º occlusion liability angle, the effect of the virtual chirp in a CD is quite evident from Figure 9. While a triangulation device would show an x:z displacement of 23º, as can be easily determined by examining the zero-order image in this reflection-type grating, the first-order diffraction image has a 42º x:z displacement with the identical occlusion liability. Without a true chirp, the target cannot be placed at a great distance, but the leverage in the y dimension caused by diffraction is evident.

5 Summary

We have previously shown that higher-order diffraction images shift relative to a central zero-order as a function of target distance. We have also previously demonstrated that we can gain control of perspective foreshortening using chirped frequency gratings. We have now demonstrated that a chirped grating placed in grazing incidence mode offers a series of improvements. We can obtain a high y to z ratio due to the anamorphic behavior of straight rule gratings. Grazing incidence affords shallower frequency chirps for equivalent perspective correction when compared with normal incidence camera to grating placement. Finally, we have achieved our primary objective in the redesign, a smaller device package. It enjoys both a reduced grating size and a much shortened stand-off from grating to camera.

Acknowledgements

Thanks to Dr. Douglas A. Lyon for his powerful DiffCAD diffraction range finder modeling program written in Java and available in his and on his website [8]. Thanks also to Kristian Buckwald of Ibsen Micro Structures A/S for the donation of the test grating.

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