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PSEUDOCOLORING METHOD FOR 3-*D* CONTOURING

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MOTS CLÉS :

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Contour

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RÉSUMÉ : Les propriétés d'interférence des diagrammes de granularité en lumière blanche obtenus avec un système optique non corrigé de l'aberration chromatique, sont appliquées à la codification en fausses couleurs des contours de niveaux d'égale profondeur d'un objet diffusant tridimensionnel. On enregistre d'abord les différentes images des niveaux de profondeur codifiées en couleur. En une seconde étape, on obtient une image faussement colorée en modifiant la position d'un filtre spatial. On peut obtenir d'ailleurs un contour quantitatif en balayant l'image faussement colorée avec un dispositif spectroscopique.

SUMMARY : The interference properties of white light speckle pattern obtained with an optical system not corrected for chromatic aberration are applied to pseudocolor encode the depth level contours of a 3-*D* diffusing object. At a first step, a recording of the different encoded images of depth levels is done. In a second step, a reconstructed pseudocolored image is obtained, where different color assignements can be tuned by changing the position of a spatial filter slit. Also, a quantitative contouring can be made scanning the pseudocolored image plane with a spectroscopic device.

INTRODUCTION

Speckle patterns produced by partially coherent white light have been theoretically and experimentally studied in the last few years [1]. Namely, the statistical properties of white light speckle have been investigated in the image plane [2-6] and in the diffraction field [7, 8]. The dependence of the speckle pattern contrast with surface roughness was established in connection with different parameters that characterize the optical system and the illuminating light : the amplitude point spread function, and the spatial and temporal coherences. K. Nakagawa and T. Asakura [9] have shown experimentally that the average contrast of the white light image speckle depends strongly on the surface roughness : for small values of r.m.s. roughness (lower than 0.5 μm) the relevant parameter is the spatial coherence, while for large values of r.m.s. roughness the effect of the point spread function is more important. When the speckle pattern is observed at a defocused plane, for an object roughness greater than 1 μm, the additional phase-noise distortion produced by defocusing does not affect much the speckle pattern contrast. On the other hand, for surface objects having a r.m.s. roughness lower than 0.3 μm, the speckle pattern contrast is affected by the phase-noise distortion due to defocusing [7].

In the present study, the interference properties of white light patterns are applied to pseudocolor encode depth level contours of a 3-*D* object. For this purpose, an optical imaging system affected by chromatic aberration with an exit pupil consisting in two identical slits, is employed. In this way, the white light speckle pattern results in pairs of tiny spectra. When both spectra of each pair intersect they do it for the same wavelength and interference Young's fringes appear in the intersection region. Therefore, at a fixed distance from the imaging lens, for each object plane there exists a coded image for a certain wavelength. This spatial codification of color information is decoded, in a further step, to obtain a depth level pseudocoloring of the 3-*D* object. On the other hand, if the rough surface is a plane one, a study of the chromatic aberration of the optical system can be done.

GENERAL CONSIDERATIONS

When a rough plane surface is illuminated by partially coherent quasi-monochromatic light, the speckle intensity distribution in the diffraction and image planes is given by

$$I(x') = \iint \Gamma(x_1, x_2)\, K(x' - x_1)\, K^*(x' - x_2)\, O(x_1)\, O^*(x_2)\, \mathrm{d}x_1\, \mathrm{d}x_2 \tag{1}$$

where $\Gamma(x_1, x_2)$ is the spatial coherence function between two different object points x_1 and x_2 that characterizes the quasi-monochromatic illuminating light; $K(x)$ is the amplitude point spread function of the optical system; and $O(x)$ is the complex amplitude of the object. For simplicity, only a one dimensional analysis is done. Taking into account the intensity fluctuations due to random phase changes introduced by the surface roughness, the above expression (1) results

$$\langle I(x') \rangle = \iint \Gamma(x_1, x_2)\, K(x' - x_1)\, K^*(x' - x_2)\, \langle O(x_1)\, O^*(x_2) \rangle\, \mathrm{d}x_1\, \mathrm{d}x_2 \tag{2}$$

where $\langle \cdots \rangle$ indicates ensemble average. The speckle pattern contrast can be defined as : $V = \langle \Delta I^2 \rangle^{1/2} / \langle I \rangle$. Therefore it should be noted that it depends on the surface roughness, the coherence conditions of the illuminating light, and the employed optical system.

When white light is used, and the optical imaging system is not corrected for chromatic aberration, different image planes appear, each one corresponding to a different color. In this way, taking into account the dispersion constant of the lens, a continuous variation of focused and defocused speckle patterns occurs. At each image plane, the amplitude point spread function $K(x)$ determines the variation of the speckle pattern contrast with wavelength, in accordance with relation (2). Therefore, using a slit as lens aperture, the resulting polychromatic speckle pattern, at a certain observation plane, consists of tiny spectra. In this case, each quasi-monochromatic speckle pattern can be treated by the general expression (2).

In this paper the interference conditions of these spectra, when a two-aperture pupil is used, are applied to obtain a mapping of depth level contours. When such a system is employed the image of a 3-*D* diffusing object consists of pairs of intersecting tiny spectra. Therefore, the intersection region exhibits Young's fringes, the spatial frequency of which is determined by the temporal frequency of the corresponding color. Because this intersection temporal frequency $\bar{\nu}$ is fixed by the specific function $n = n(\lambda)$ that describes the chromatic aberration of the lens, as $\bar{\nu}$ takes all values of the visible spectrum, different planes are characterized for a given fixed image plane. Thus, a pseudocolor encoding of level contours of a 3-*D* object can be obtained.

DESCRIPTION OF THE METHOD

In the method we present here, the optical system consists of a white light source S_0 limited by a diaphragme *D*, an achromatic lens L_1, and a second lens L_2 not corrected for chromatic aberration whose pupil consists of two laterally displaced slits R_1 and R_2 symmetrically located to the optical axis of the system. This arrangement is shown in *figure 1*. For a given $\bar{\lambda}$ characterizing a certain band of the spectra, the amplitude point spread function $K_i(x', y')$, at the image plane, is the smallest spread diffraction pattern of one slit modulated itself by Young's fringes. Namely,

$$K_i(x', y'; \bar{\lambda}) = f_i(x', y'; \bar{\lambda}) \left[1 + \cos\left(\frac{2\pi x'}{p} + \Phi \right) \right] \tag{3}$$

where $f_i(x', y'; \bar{\lambda})$ takes into account the slit diffraction pattern at the image plane corresponding to $\bar{\lambda}$-wavelength; $p = d/\bar{\lambda} z_i$, is the spatial frequency of Young's fringes; and Φ is a constant phase delay. Because of the chromatic aberration of the employed optical system, the image point spread function for each $\bar{\lambda}$ lies in a different plane in accordance with the relationship : $n = n(\bar{\lambda})$.

Thus, for a given object distance z_0, the image distance $z_i(\bar{\lambda})$ for each $K_i(x', y'; \bar{\lambda})$ results

$$z_i(\bar{\lambda}) = \frac{C z_0}{z_0[n(\bar{\lambda}) - 1] - C}$$

where $1/C$ is the geometrical bending parameter that characterizes the lens L_2.

The white light speckle pattern of a plane diffusing object is observed at a fixed plane π', such that the image point spread functions $K_i(x', y'; \bar{\lambda})$, corresponding to several wavelengths $\bar{\lambda}$, lie in planes near π'. In this way, only for a color represented by a certain wavelength $\bar{\lambda}^{(i)}$, $K_i(x', y'; \bar{\lambda}^{(i)})$ lies in the π'-plane. For all other wavelengths $\bar{\lambda}$, the point spread functions $K_d(x', y'; \bar{\lambda})$ are broader than $K_i(x', y'; \bar{\lambda}^{(i)})$ in the π'-plane. Therefore, an expression of $K_d(x', y'; \bar{\lambda})$ can be given as

$$K_d(x', y'; \bar{\lambda}) = f_d(x', y'; \bar{\lambda}) \left\{ 1 + \gamma[z_i(\bar{\lambda})] \cos\left(\frac{2\pi x'}{p} + \Phi \right) \right\}$$

where $f_d(x', y'; \bar{\lambda})$ takes into account the slit diffraction pattern at the defocused plane π'. The attenuation factor $\gamma\ [z_i(\bar{\lambda})]$ of Young's fringes is originated by

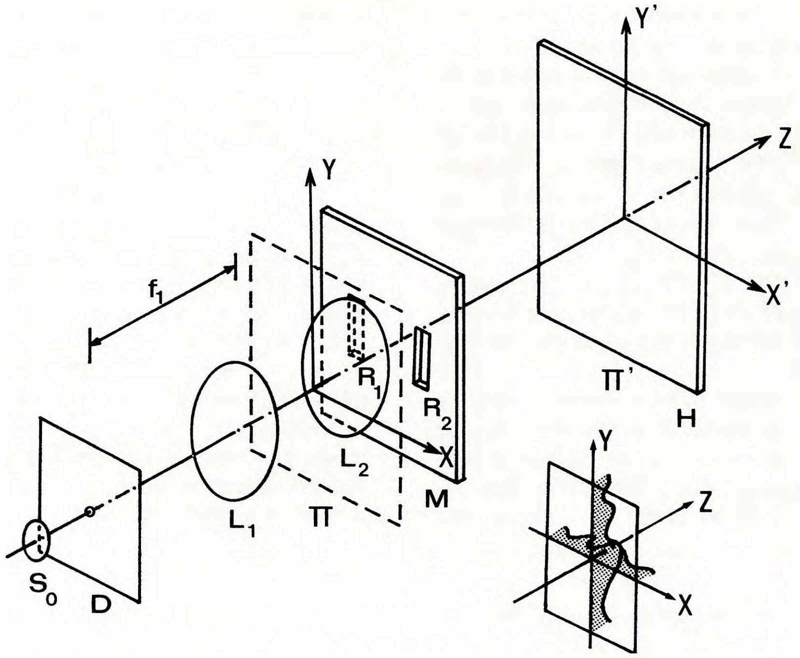

FIG. 1. — *Schematic diagram of the experimental set-up used in the registering step. Due to chromatic aberrations, L_2 conjugates π-plane and its surroundings (which are shown in detail in the lower part of the figure) with π'-plane.*

the limited spatial coherence of the light source S_0. Neglecting Young's fringes with visibility values lower than the corresponding to the condition :

$$K(x\,;\Delta z_i) = 0\,, \quad \text{for} \quad x > L_c\,,$$

the attenuation factor $\gamma\,[z_i(\bar{\lambda})]$ may be assumed as

$$\gamma[\Delta z_i] = 1 - \frac{|\,\Delta z_i\,|}{\alpha}. \tag{4}$$

In the above expressions, L_c denotes the spatial coherence length (which is determined by the Van Cittert-Zernike theorem), and Δz_i is the distance between the π'-plane and the image plane associated with $\bar{\lambda}$. Assuming a geometrical behavior of $K(x\,;\Delta z_i)$, an expression for α can be given as

$$\alpha = mL_c\, z_0(\bar{\lambda}^{(i)})/d\,.$$

where m is the longitudinal magnification, d is the separation between R_1 and R_2, and $z_0(\bar{\lambda}^{(i)})$ is the object distance of the π-plane. Therefore, for a certain image plane such that

$$z_i(\bar{\lambda}^{(i)}) - \alpha > z_i(\bar{\lambda}) > z_i(\bar{\lambda}^{(i)}) + \alpha,\ \gamma(\Delta z_i) \simeq 0\,,$$

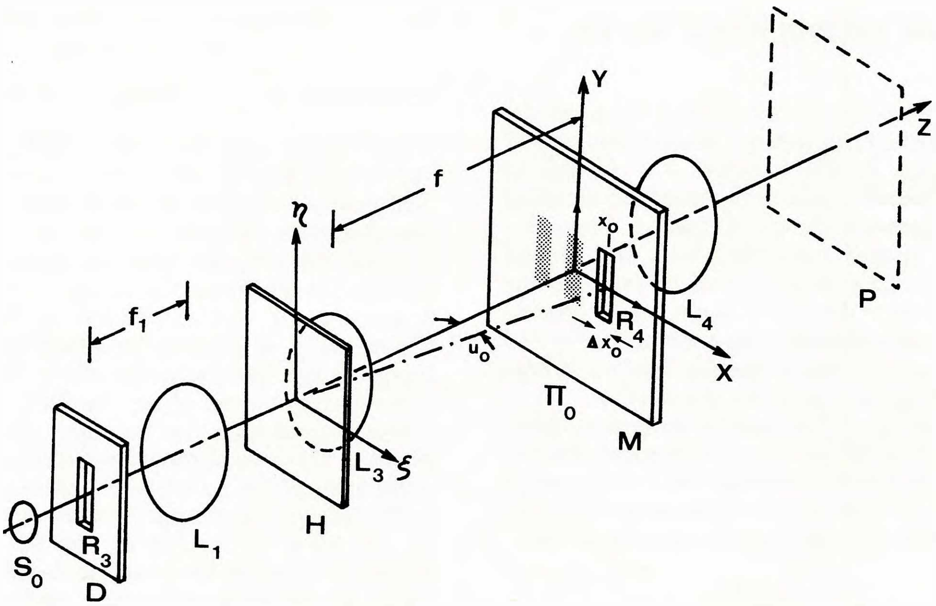

FIG. 2. — *Schematic diagram of the experimental set-up employed in the decodification step. P represents the output plane.*

and no fringes appear in the diffraction pattern corresponding to the color characterized by $\bar{\lambda}$.

Therefore, when a 3-*D* diffusing object is considered, every object plane is imaged in a certain color which is associated to a given wavelength $\bar{\lambda}$ at the π'-plane. In this way, the different point spread functions $K_i(x', y'; \bar{\lambda})$ that are present in π' determine the existence of Young's fringes whose spatial frequencies belong to a certain band $\Delta p = (d/z_i)(1/\bar{\lambda}_1 - 1/\bar{\lambda}_2)$. These cut-off wavelengths $\bar{\lambda}_1$ and $\bar{\lambda}_2$ are determined both by the spectral content of the white light source, and by the spectral sensitivity response of the recording material to be used.

A recording of the white light « image » speckle pattern is done at the π'-plane. After processing, the photographic plate H is placed in the optical arrangement shown in *figure 2*. An achromatic lens L_3 images the slit R_3 at its focal plane π_0. Taking into account the recorded intensity in H, the amplitude distribution $U_0(u, v)$ in the π_0-plane, is

$$U_0(u, v) = \int d\lambda \iint d\xi \, d\eta \, t(\xi, \eta) \, e^{-(2\pi i/\lambda)(u\xi + v\eta)} \tag{5}$$

where $u = x/f$, $v = y/f$, and f is the focal length of L_3; $t(\xi, \eta)$ is the amplitude transmittance of H, at (ξ, η)-plane. The integration over λ involves all wavelengths of the reconstructing white light source.

Let us consider a certain spatial frequency value $u_0 = x_0/f$ that characterizes the location, at π_0-plane, of one diffracted order of Young's fringes for a certain wavelength λ_0. A spatial filter slit R_4 is placed in π_0-plane located at $u = u_0$. Taking into account the spatial spectrum of $t(\xi, \eta)$, the expression (5) can be rewritten as follows,

$$U_0(u, v) = \text{rect}\left[(u - u_0) f/\Delta x_0\right] \int d\lambda \left[T(u/\lambda, v/\lambda) * (\delta(u/\lambda, v/\lambda) + \delta(u/\lambda - u_0/\lambda_0, v/\lambda) + \delta(u/\lambda + u_0/\lambda_0, v/\lambda))\right]. \tag{6}$$

In expression (6), $T(u/\lambda, v/\lambda)$ is the spatial spectrum of the amplitude transmittance $t(\xi, \eta)$ for a given wavelength, regardless the spatial modulation introduced by Young's fringes; rect $[(u - u_0) f/\Delta x_0]$ is the rectangular function associated with the spatial filter R_4. Finally, the δ-functions locate the three diffracted orders 0, ± 1 of Young's fringes.

The slit width Δx_0 of R_4 determines both the spatial spectral band of the 3-*D* object image for a certain wavelength that is transmitted to the final image, and the frequency spectral band that encodes each Young's fringes spatial frequency. In this way, R_4 acts as a temporal-spatial filter; that is : as the slit width Δx_0 decreases, the image of each depth level of the 3-*D* object exhibits a well defined color, but its finer details vanish in the final image.

PSEUDOCOLOR ENCODING OF DEPTH LEVELS

As we stated above, a pseudocolored image of the 3-*D* object is obtained employing a second lens behind the spatial filter slit R_4. Nevertheless, it is possible to carry out a preliminary real time visualization using the optical arrangement shown in *figure 1*. The color of the Young's fringes associated with the several image planes acts as a primary tool to evaluate the depth level contours of the object, and it can be observed with a microscope focused in the π'-plane. In *figure 3* is shown the polychromatic speckle pattern where Young's fringes appear only for green color.

When a recording of this speckle pattern is done, the spectral range of the pseudocolored reconstructed image is determined by the spectral band of the image planes that are focused on the photographic plate. The different color encoding planes are related by,

$$\sin\theta = \frac{\lambda_0 \, d}{\lambda_r \, z_i} \tag{7}$$

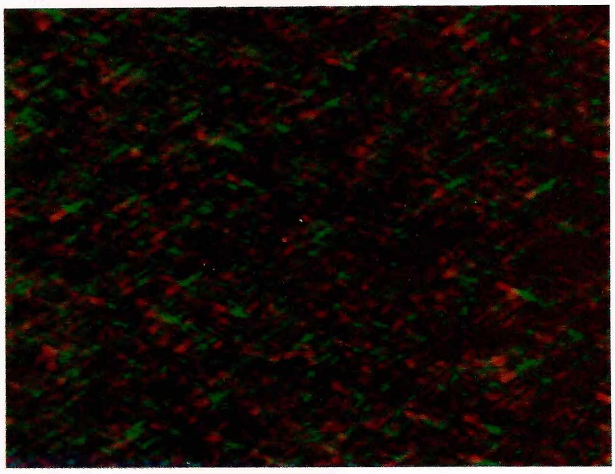

FIG. 3. — *Polychromatic speckle pattern. Young's fringes appear only for green color.*

where θ is the angular position of R_4, λ_0 is the observation wavelength, and λ_r is the recording wavelength. In this way, changing the value of θ it is posible to tune the chromatic interval, so that the colors originally focused on the photographic plate appear in the pseudocolored image. Other false colors, ruled by the expression (7), can be selected in the coded image. Therefore, it is possible to obtain a pseudocolored image in the spectral range where better human eye color discrimination occurs. Besides, if a spectroscopic device is used such that the input slit is placed in the plane of the reconstructed pseudocolored image, the contouring of the 3-*D* object, in the input slit direction, is displayed in the output plane of the analyzer device. In this case, the profile of the 3-*D* surface can be obtained scanning the pseudocolored image with the slit of the spectroscopic device, and with appropriate calibration a quantitative contouring can be made.

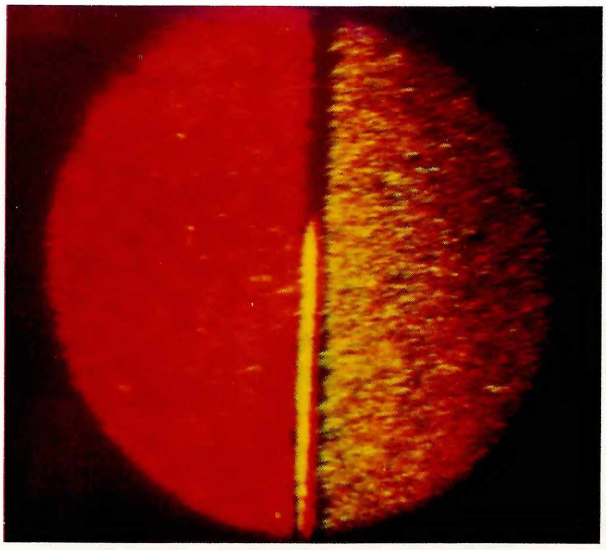

FIG. 4. — *Experimental result.*

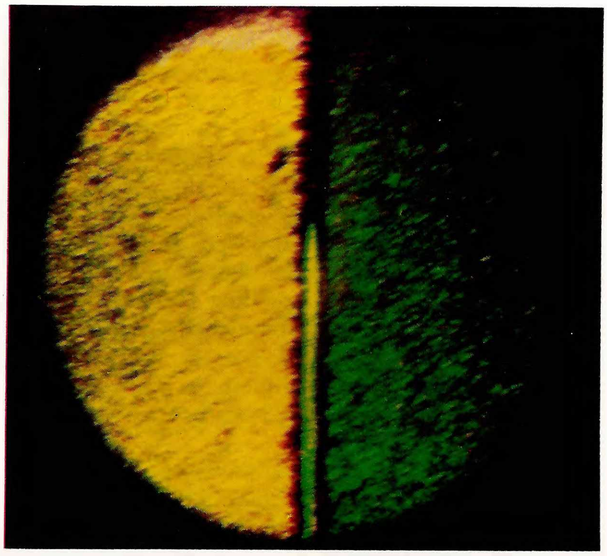

FIG. 5. — *Experimental result.*

In *figure 4* and *5*, experimental results are shown corresponding to an object composed of two plane rough surfaces, one of which is normal to the optical axis, and the other one lies in a tilted and axially shifted plane. The angle of tilt was 3°, and the shift was of 2 mm. Both photographs were taken for two different positions of the spatial filter slit R_4. In this way, two different pseudocolored images of the same object are obtained. The optical frequency difference $\Delta\nu$, corresponding to the colors associated with each plane, is,

$$\Delta\nu = \nu_2 - \nu_1 = k/\sin\theta$$

where k is a constant given by : $k = c(1/\Delta_2 - 1/\Delta_1)$; c is the vacuum light velocity; Δ_2 and Δ_1 are the spacings of Young's fringes corresponding to each plane. Therefore, a greater chromatic difference is obtained by placing the slit R_4 in the region of shorter wavelengths.

3-*D* RECONSTRUCTION CAPABILITY

As it has been pointed out before (Eq. (7)), the reconstructed image can be obtained with the same colors that were properly focused on H in the registering step. If H is replaced in its original location and the reconstruction is done as it is indicated in *figure 6*, light rays actually travel the inverse path. In this way, a 3-*D* image of + 1 magnification of the original object can be obtained in its original position. In this case geometrical aberrations are cancelled. Nevertheless, due to the presence of a narrow slit, depth of field is large and resolution is severely limited. Because of this, the 3-*D* nature of the images is difficult to observe experimentally. At present, we are intending to overcome these shortcomings.

The pictures shown in *figure 4* and *5* were actually obtained in this way, and a slight missfocusing can be observed in the left side of the images.

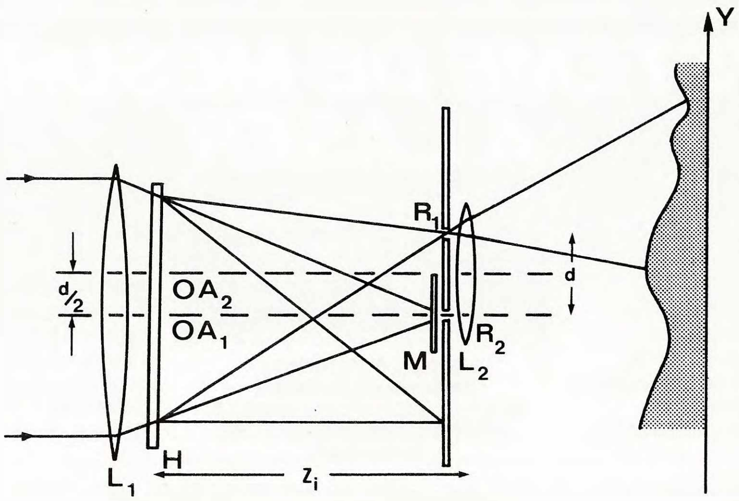

FIG. 6. — *Schematic diagram of the experimental set-up employed for 3-D reconstruction. OA_1 : optical axis of the achromatic transforming lens L_1, centered at R_2 slit position. OA_2 : optical axis of the not corrected lens L_2. M : mask to block the undesired « 0 order ».*

CONCLUSIONS

In this paper we have applied the interference properties of white light speckle pattern obtained with an optical system not corrected for chromatic aberration to pseudocolor encode the depth level contours of a 3-*D* diffusing object. Due to the special optical arrangement employed the resulting polychromatic speckle pattern consists of tiny spectra with a spatial fringe modulation determined by the optical frequency corresponding to the intersection of spectra. In this way, a spatial encoding of an object-space determined by the amount of axial chromatic aberration of the optical system, is accomplished. In a further step, a pseudocolored image is obtained through a temporal-spatial filtering operation.

This method allows the false colors to be tuned; i.e. varying the location of the slit R_4 is possible to select different color assignements. In this way, any particular zone of interest of the object can be tuned in order to be shown in the color of maximal human eye discrimination. Also, in the case of a continuous variation of depth, a continuous color encoding is obtained. However, the useful volume is small as it is limited by the amount of axial chromatic aberration. Because of the finite size of the involved slits, image resolution is limited in one direction.

Alternatively, if a plane rough surface is used as object, both the axial chromatic aberration and the lateral chromatic aberration may be studied.

* * *

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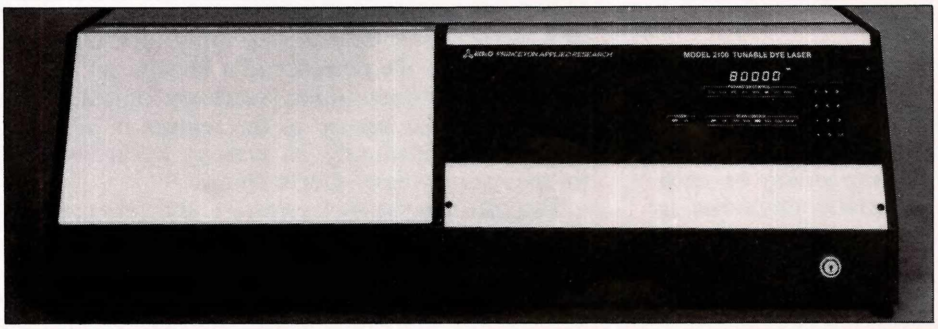

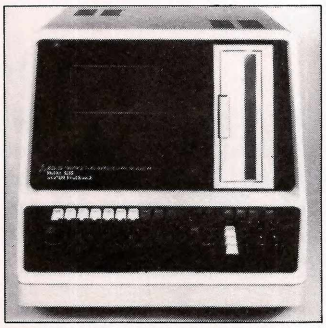

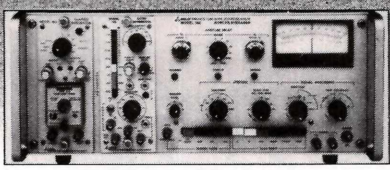

Pseudocoloring method using two different spatial modulations

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Pseudocoloring of gray level information is a technique for introducing false colors in a black-and-white transparency. The importance of this operation is based on the human eye's ability to distinguish different colors better than gray levels. In the last few years several pseudocoloring optical methods have been proposed.[1-10] Furthermore, the pseudocoloring technique has been extended to encode image spatial spectral bands[11-13] and holographic interferometric fringe patterns.[14] In a recent paper[15] we presented a further generalization of pseudocoloring for assigning false colors to depth level contours of 3-D objects.

In this Letter we propose a modification of the pseudocoloring speckle method[9] for storing two images in a single recording material in such a way that each recorded image has a different spatial modulation. Therefore, in a decoding step, on illuminating the processed plate with a white light source, there exist two wavelength values for which the spatial spectra of both encoded images are centered at the same spatial frequency value. Thus, an additive mixture of both images is produced with a pseudocoloring effect which depends on the two mentioned wavelengths.

The scheme of the optical arrangement utilized in the encoding step is shown in Fig. 1. The image of a certain scene E_1 is recorded by using as a lens pupil a double aperture of separation d_1. This causes a spatial spectra shift Δu_1 given by $\Delta u_1 = d_1/\lambda D$, where λ is the light wavelength, and D is the image distance. Afterward, a record of the image of another scene E_2 is done in the same plate but now using as a lens pupil a double aperture of separation d_2. Thus, the spatial spectra shift Δu_2 is given by $\Delta u_2 = d_2/\lambda D$.

The decoding step is shown in Fig. 2. The developed plate H is illuminated with a collimated white light beam. Then, for a certain value of the viewing angle θ, there exists a superposition of the E_1 and E_2 images in the colors given by the corresponding wavelengths λ_1 and λ_2 such that, $d_2/d_1 = \lambda_1/\lambda_2$ In this way, all the common parts of the E_1 and E_2 images are pseudocolored by a color mixture which depends on λ_1 and λ_2.

So far no relation exists between E_1 and E_2. However, if E_1 and E_2 images are complementary (for object transparencies, the positive and negative images), the image resulting from the superposition is a pseudocolored one of either E_1 or E_2. The corresponding contrast reversed image can be obtained employing the method of Ref. 10, that is, recording the light scattered from the silver developed grains that form the original image transparency. An alternative approach consists of employing the optical subtraction technique through Young's fringes modulated speckle.[16] In this case, a first record of the image of a speckle pattern is made. Then the image of the same speckle pattern is recorded but modulated by the object transparency E_1, introducing a π-phase delay between both exposures. Thus, a contrast reversed image of E_1 is obtained.

Another case of interest arises when the image of E_2, instead of being the complementary one of E_1, is a modified version of it. In this case, the third pseudocolor encodes the common

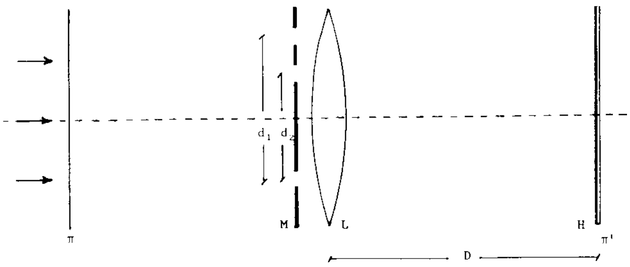

Fig. 1. Experimental setup of the encoding step: M, mask; L, lens; H, photographic plate; π and π', conjugate planes.

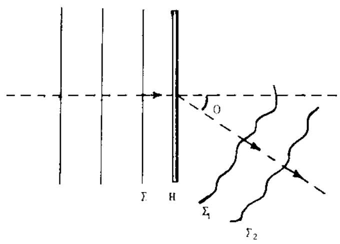

Fig. 2. Scheme of the decoding step: Σ is a collimated white light beam; Σ_1 and Σ_2 are the diffracted waves corresponding to λ_1 and λ_2.

regions of both scenes. Some experiments have been done using as E_1 the isochromatic fringe pattern that appears in a loaded photoelastic model. The scene E_2 corresponds to the complementary fringe pattern (obtained by rotating the polarization state of the incident light by 90°) but with a different loading condition. Therefore, in the decoding step, the resulting moire pattern appears in a pseudocolor given by the mixture of λ_1 and λ_2.

Finally, another point of interest for this pseudocolor encoding consists of studying the spatial changes in one direction of an object transparency. In this case, the E_2 image is a shifted version of the E_1 image. The amount of shifting depends on the size of the finest details to be studied. Thus, the sign of the gray level change is coded by a spectral color which corresponds to λ_1 or λ_2.

In summary, we have presented a simple method for generalizing the speckle pseudocoloring technique to include other cases besides gray level pseudocoloring. An advantage of this method consists of employing colors, given by λ_1 and λ_2, that are spectral. When using green and red as false colors, as usual, it is possible with this method to obtain a third color which lies in a straight line in the chromatic diagram, very close to the locus of the spectral colors. In this way, false colors of high purity are obtained.

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