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H4.SMR/452-59

ADRIATICO CONFERENCE ON
FOURIER OPTICS AND
HOLOGRAPHY

6 - 9 March 1990

SPECKLE PHENOMENA

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Speckle Phenomena

Speckle:
- coherent illumination
- diffuse object (piece of paper, cement surface, etc)
- interference + diffraction

Originally, speckle appears as noise causing degradation in the recording of a holographic image.

Denis Gabor: "The novelty in holography is speckle noise. This has really nothing to do with holography, it is a consequence of coherence. It has an special standing among noise phenomena because it is not really a noise, but unwanted information....".

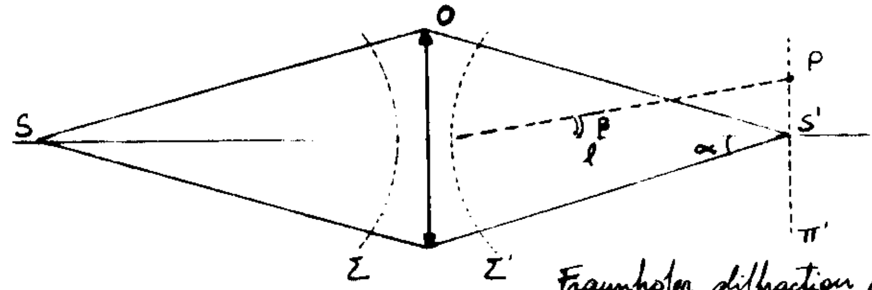
Speckle was sensitive to movements (moving diffuser).

Burch and Tokarski [Optica Acta, 15, pp. 101]

- Brief physical introduction to speckle.
- Roughness.
- Image optical operations.
- Speckle correlation (the joint transform correlator).
- Speckle and the display of coherence.
- Speckle and periodicities.
- Speckle as 3-D display.
- Velocimetry by using speckle patterns.

Physical Introduction

Point source image



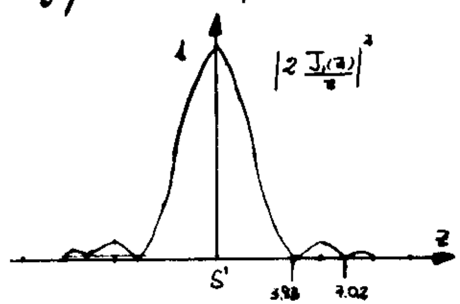
Fraunhofer diffraction pattern

The structure is calculated by the Huygens-Fresnel principle ⇒ Fourier transform (spectrum)

Example: limiting circular aperture, the amplitude is given by

$$A(\beta) = \frac{2J_1(ka\beta)}{ka\beta} \qquad (1) \qquad 2a = \text{diameter},\; k = 2\pi/\lambda$$

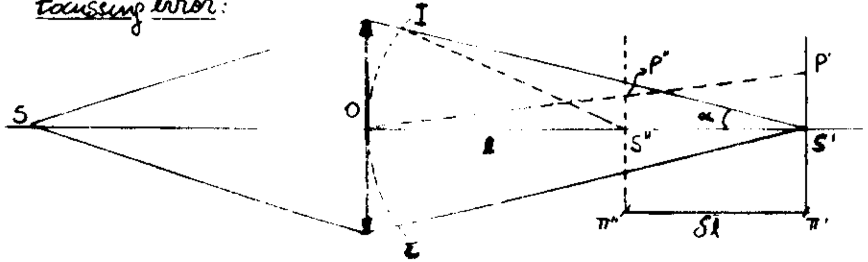
The resulting intensity pattern $|A(\beta)|^2$ is



Airy disk

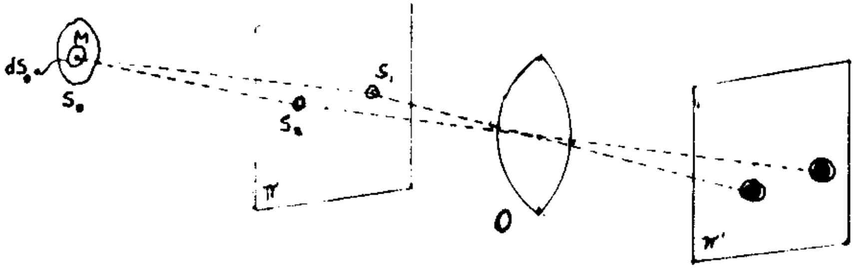
From the Bessel function, the angular radius of the first ring is $\beta = \frac{1.22\lambda}{2a}$

Focussing error:

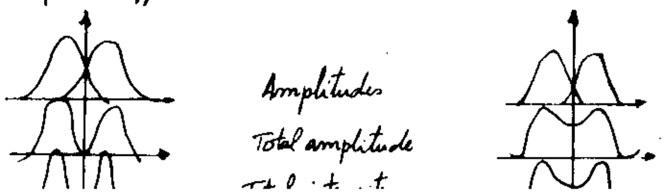


At focus all vibrations are in phase, at S'' not. The maximum optical path difference at S'' is $\Delta = IS'' - OS''$ or $\Delta = \delta l \alpha^2/2$. We define S'' identical to S' when Δ does not exceed λ, that is $\delta l \ll 2\lambda/\alpha^2$

Two monochromatic point sources

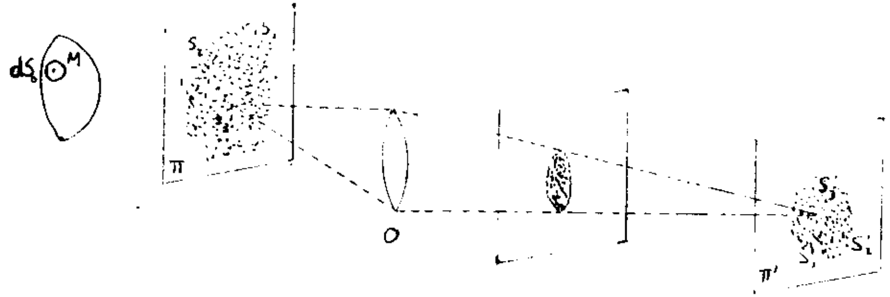


The optical path difference is $\Delta = MS_1 - MS_2$, and the phase difference $\varphi = 2\pi\Delta/\lambda$. When S_1 and S_2 are illuminated by dS_0 are said to be coherent. The phenomenon in π' depends on φ [the amplitudes must be added]. If $\varphi = \pi$, both amplitudes are substracted. By taking another dS_0', phase change, but diffraction image not, and intensity will change. If S_1 and S_2 are simultaneously illuminated by dS_0 and dS_0', there is not phase relationship between them, they are incoherent, and in such case the intensities of the diffraction images must be added.



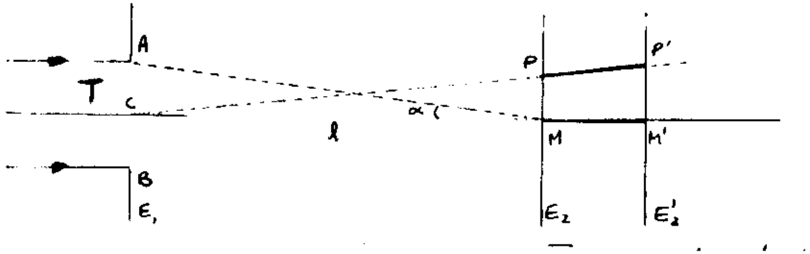
Consider now the operation is performed for all dS_0 on S_0: intensity distribution at π' is equal to the one obtained when the two diffraction images are added. When illuminated by an extended source S_1 and S_2 behave like two incoherent sources, the intensity is found by adding the intensities of the two diffraction images produced separately by S_1 and S_2.

Large number of point sources distributed at random



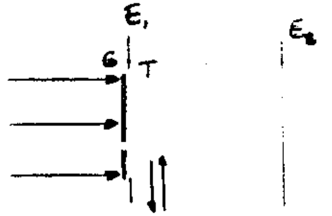
Each aperture diffract the light as coherent light sources, giving at π' an Airy disk. All amplitudes are added taking into account the phase relationships. A quite complicate structure is obtained, the smallest spot having a diameter equal to that of the diffraction spot of lens O. This granular structure is called speckle. As dS_0 is increased, the elements behave as quasi-coherent sources decreasing the contrast of speckles. For the whole source S_0, the contrast tend to zero and speckles disappears, being the sources incoherent.

Fresnel and Fraunhofer diffraction in 3-D

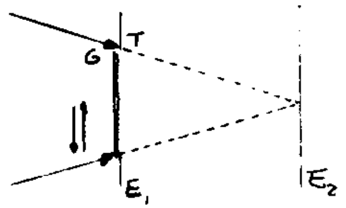


Intensity at M results from the contribution of all points belonging to T. The optical path difference $\overline{MA}-\overline{MC}=\Delta=a^2/2l$, then the phase values are between 0 and Δ. A variation δl cause a phase difference by $a^2\delta l/2l^2$. If M and M' must be the same, this change must be smaller than λ. if $\alpha = a/l \Rightarrow \delta l \ll 2\lambda/\alpha^2$ ⊕
Under this condition the Fresnel pattern at E_2 is similar to the one at E_2'. It is also shown that the structure changes more slowly as the distance E_1E_2 increases. When δl can take practically any value we pass to the domain of Fraunhofer diffraction. If a screen with small holes is placed at T, light will be diffracted and spread out at E_2, then another speckle pattern will appear. Under ⊕, a change to E_2' produce a scale factor. According to this, speckle patterns are classified as Fresnel-Type for intervals $\overline{E_1E_2}$ with finite length, and Fraunhofer-Type when $\overline{E_1E_2}$ increases indefinitely. The same is valid for a diffuse reflecting object, where the surface irregularities give rise to a phenomenon similar to the small holes, with wider spread as smaller the irregularities. For a ground glass in T, the smallest speckle diameter is given by $\varepsilon = l\lambda/a$, independent of the structure of the object. The spatial distribution depends on such structure.

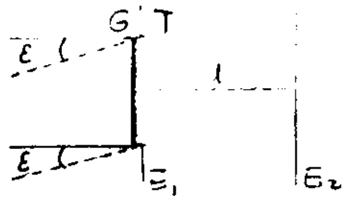
<u>Speckle shifting</u>



Lateral shift

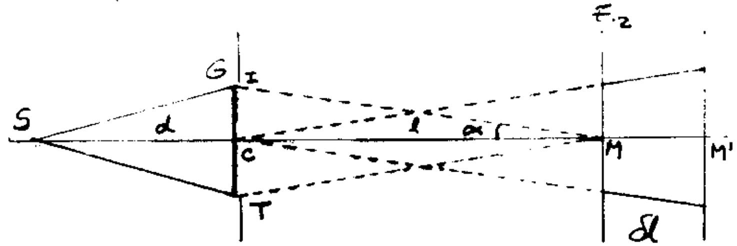


In the case the beam converges to E without G ("Fourier plane"), no alteration is seen when moving G. A constant phase is added and the intensity distribution remains the same. The same holds for a reflecting diffuse object.



orientation of the beam

The speckle pattern remains identical only translated εl



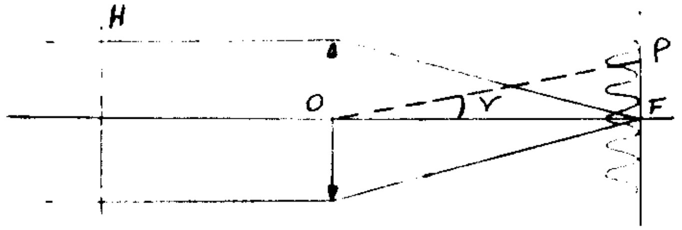
Axial translation

If $\delta l \ll 2\lambda/\alpha$ is satisfied $\Rightarrow$ two correlated speckles (scale factor)
Also by $\Delta\lambda$, or illuminating a diffuser with another speckle pattern.
Summarizing: a movement of G $\Rightarrow$ scale change, depending on the amount of the displacement of the object.

<u>The fundamental experiment of Burch and Tokarski</u>

$D(\eta,\xi)$ normal speckle distribution
Double exposure H + Displacement ξ_0
The recorded intensity is $D(\eta,\xi)+D(\eta,\xi-\xi_0)$
or $D(\eta,\xi) \circledast [\delta(\eta,\xi)+\delta(\eta,\xi-\xi_0)]$ +

the intensity transmitted after development is proportional to +



At focal plane $\tilde{D}(u,v)[1 + \exp(i\pi\gamma\xi_0/\lambda)]$ $\tilde{D} = FT[D]$

$I \propto |\tilde{D}(u,v)|^2 \cos^2(\frac{\pi\gamma\xi_0}{\lambda})$ (speckle background)

Orientation of fringes give information about the direction of the movement.

ESPI = Also data can be collected by a T.V. camera and electronically processed [Leendertz]

Roughness

Mechanical profilometer - stylus $V(h)$

Drawbacks 1: contact method (damage surface)

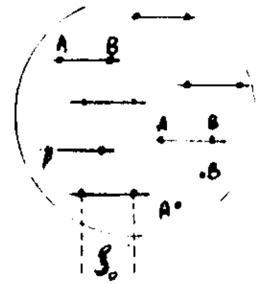
2: 1-D information

Optical techniques - contrast of speckles - statistical properties of speckle intensity variations

Optical processing

A, B photographs, A−B is required (remove features that remains unchanged)

Both are copied on H illuminated by speckle + ξ_0

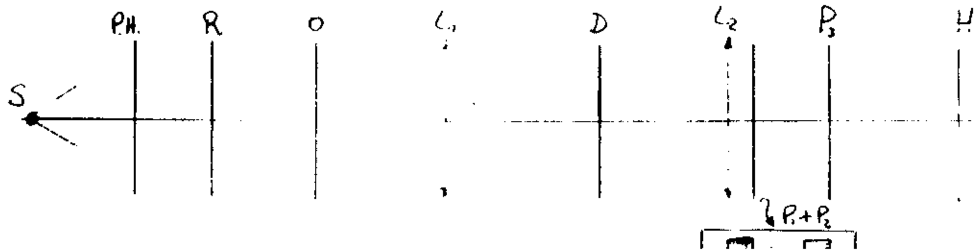


Areas with identical grains give rise to Young fringes. Slit filters the information.

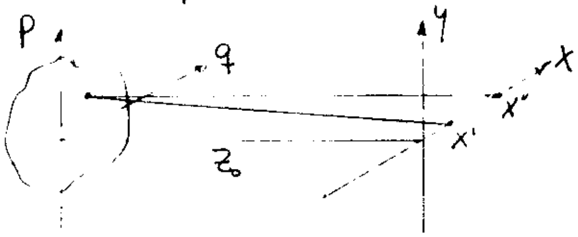
Optical Operations

Young fringes modulated speckle pattern: Multiple apertures (shear)

Array of polarizers (λ-independent) _ Color operations (partially coherent white light)



Speckle patterns and optical periodicities.



Coherent light propagation → diffraction. Temporal coherence → spectral profile of the source. According to VC-Z, the mutual intensity (degree of spatial coherence)

$$J(x', x'') = \exp(i\alpha)\ FT[I(p,q)]$$

$\alpha = k(x'^2 - x''^2)/2z_0$ $\qquad I(p,q)$ = intensity function of the source

Spatial periodic source: multiple exposed speckle pattern (shifted s)

$$I(p,q) = I_0(p,q) * \sum_m \delta(q - ms) \quad ; \quad I_0(p,q) = \text{single speckle pattern}$$

(A) $J(x', x'') = \frac{\tilde{I}_0}{(\lambda z_0)^2} \exp\left(\frac{x'^2 - x''^2}{\lambda z_0}\right) \sum_m \exp\left(\frac{2\pi i m x' s}{\lambda z_0}\right)$ on a plane G, at z_0

If a grating is placed at G $\quad g(x') = \Gamma_0 \sum_m \exp(2\pi i m x'/d)$ (B)
d = period of grating

By comparing (A) and (B), the slits of grating are coherently illuminated if:

$$z_0 = \left(\frac{n}{m}\right) \frac{s d}{\lambda}$$