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Spatial pulse response in photographic relief images

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Experimental measurements of the relief pulse response of the photographic emulsion Kodak 649F has been made. The width and amplitude of the light pulse were taken as variables. It has been proved experimentally that lateral shrinkage effects cause a rise of the relief height in regions, where spatial derivatives of the emulsion density do not equal zero. The optimal relation between the pulse and the relief shapes occurs when the pulse width is approximately twice higher than the emulsion thickness.

1. Introduction

Photographic relief effects are well known in photography. In general, the nature of the formation of photographic relief images is explained as an emulsion-thickness variation due to the gelatin shrinkage around the silver deposits. Since this thickness variation may result in a spatial phase modulation of coherent light, the relief image can find an important application in coherent light optics, like reflection holography. Relief images can be also applied as matrices for making contact replicas of holograms.

A systematic and comprehensive study of the formation and control of photographic relief images has been made by Smith [1], in Eastman Kodak Company Research Laboratory. This excellent work should be mentioned more extensively. Smith tested a very fine-grained emulsion, similar to 6451 Kodak Minicard Film. The exposure of the emulsion was sinusoidal, of the following form

$$E(x) = E_0(1+M\cos\omega_0 x), \tag{1}$$

where E_0 — the average exposure,
M — the modulation coefficient,
ω_0 — the radian spatial frequency.

Several exposures were made for each spatial frequency ranging from 2.5 to 200 lines per millimeter, in order to obtain several values of the peak-to-peak density variation:

$$\Delta D = D_{max}-D_{min}. \tag{2}$$

After determining the ΔD values for each sample and each spatial frequency, the relief-image heights were measured by means of a Twyman–

Green interferometer. From the results of Smith's measurements it follows that for each frequency the relief height is approximately proportional to the peak-to-peak density variation, but the proportionality varies: at first, it increases up to a certain maximum, then it decreases with the spatial frequency. The relief height vs. the spatial frequency, with ΔD, as a parameter is shown in fig. 1. It has been experimentaly

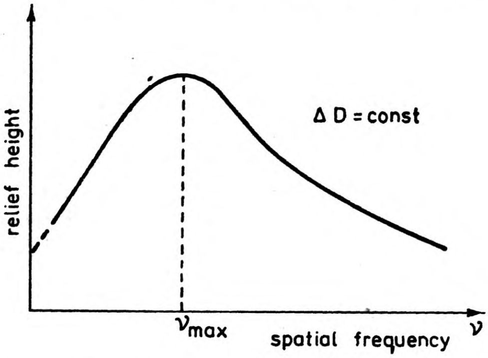

Fig. 1. The relief height vs. the spatial frequency at ΔD, as a parameter

found, that the frequency ν_{max} depends only on the thickness of the emulsion, being inversely proportional to the thickness. From the data presented in Smith's report a simple relation may be determined

$$\nu_{max} = 170/d, \tag{3}$$

where d is the thickness of the emulsion in micrometers. This relation is valid at normal photographic processing of the emulsion. Experimental measurements of Kodak 649F spectral plates, presented by LAMBERTS in [2] have fully confirmed the results obtained by Smith.

The fact that the height of the relief varies with spatial frequency under the same energetic exposure conditions seems to imply that a simple explanation of relief formation in terms of bulk silver is not sufficient. If we extend the Smith's diagram, approximating it up to the zero-frequency point, then we get a value of relief height, which corresponds to such a simple explanation of bulk silver. Higher values of the relief height can be explained in terms of lateral shrinkage forces, which cause the lateral movement of the emulsion, pulling up the gelatin in regions of higher densities. The lateral shrinkage forces are probably linearly dependent on the space derivative of the density, which seems to explain, why the height of the relief depends linearly on the spatial frequency within the low frequency range.

Both SMITH and LAMBERTS [1, 2] in their relief experiments used the same routine camera intended for modulation-transfer-function measurements. In general, the modulation-transfer-function is a spectral representation of transmitting properties of any of information transmitting system. If it is a linear system, then its pulse response does not depend on the level of the input signal, and the spectral properties of the system, described by the modulation-transfer-function and being the Fourier transformation of the pulse response, do not depend on the input signal level, either. In process of relief formation strong nonlinearities occur and it is impossible to describe its transmitting properties in terms of modulation-transfer-function.

2. The measurements of the pulse response in the relief formation process

In order to investigate the pulse response in the process of relief formation a wedge-shape mask was prepared which allowed to achieve the spatial light zero-one-zero pulse of a variable width ranging approximately from zero to 300 μm. The mask was evaporated on an optical plane-parallel glass plate. As a material to be tested Kodak 649F spectral plates were used, the emulsion thickness being about 15 μm.

The mask and the emulsion were coupled in a special vacuum box, which ascertained tight contact between the mask and emulsion surfaces.

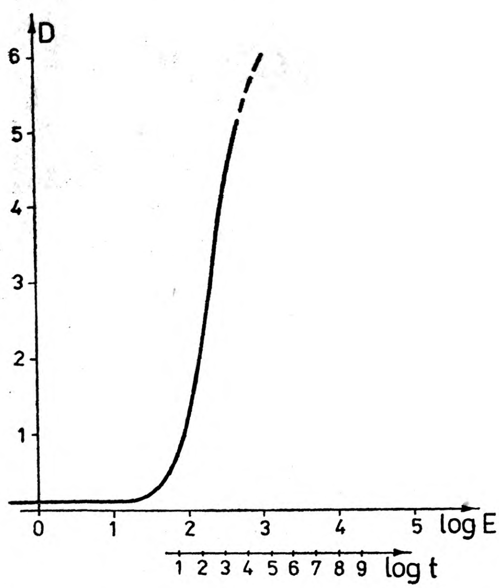

Fig. 2. Situation of the nine measurements points on the D–lg H characteristic of 649F Kodak plates

A part of the plate was not masked in order to get the area for density measurements.

The exposure range was much higher than in Smith's and Lambert's measurements. The times of the exposures were aligned in the geometrical progression order from 2 to 512 seconds. The corresponding exposure points are shown in fig. 2. The density of the 16-sec. exposure was unmeasurable — it was higher than 5.

After exposing nine plates of the dimensions 3×4 cm, cut from the same 9×12 cm plate, all the plates were simultaneously processed: they

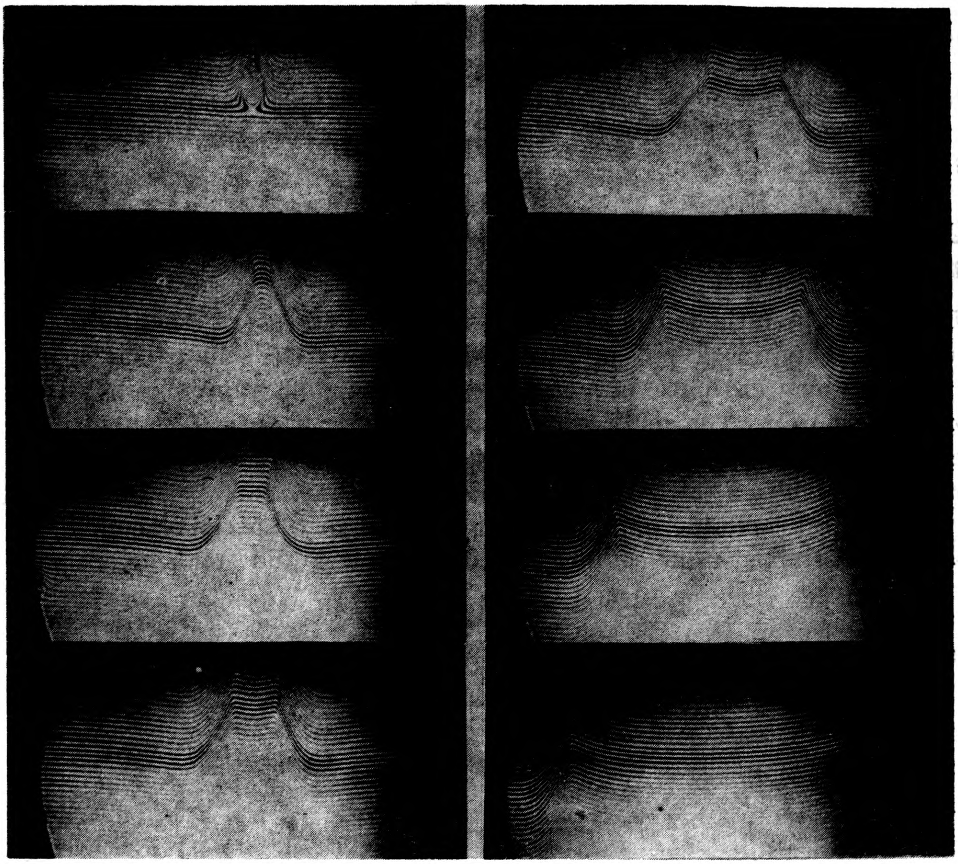

Fig. 3. The fringe patterns corresponding to the 128-sec. exposuré and different widths of the light pulse

were at first developed in Kodak HRP developer at 293 K for 8 min., rinsed for 30 sec. in distilled water and fixed in Kodak Fixing Bath F-5. The plates were washed in distilled water for 30 min. and dried at room temperature.

The relief profiles were measured in a Twyman–Green microinterferometer used in conjugation with a microscope. The surface of the emulsion played the part of one mirror of the interferometer. The other mirror was adjustable for path-length variation and tilted about two axes. As a light source a filament lampe in conjunction with 590 nm interference filter was used.

The fringe patterns corresponding to the 128-sec. exposure and different widths of the light pulse are shown in fig. 3.

In order to determine the shape of the relief pulse response, the following denotations were assumed:

a — the width of the zero-one-zero pulse,

b — the peak-to-peak height of the relief,

c — the middle recess of the pulse response,
d — the external recess of the pulse response,
e — the width of the intermediate region,
f — the distance of lateral outside shrinkage forces, measured between the edge of the light pulse and the point, where the outside recess nearly equals $1/8\lambda \cong 75$ nm.

A schematic representation of the parameters determining the shape of the relief pulse response is shown in fig. 4.

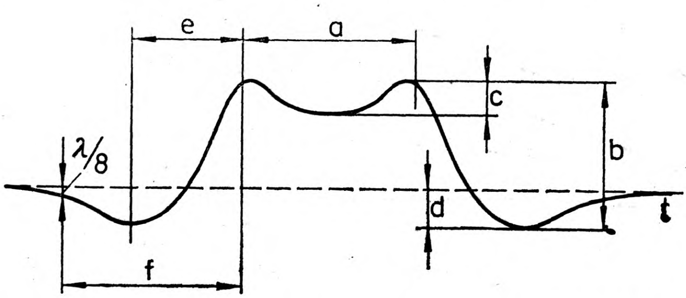

Fig. 4. Schematic representation of the parameters determining the shape of the relief pulse response (for notations see text)

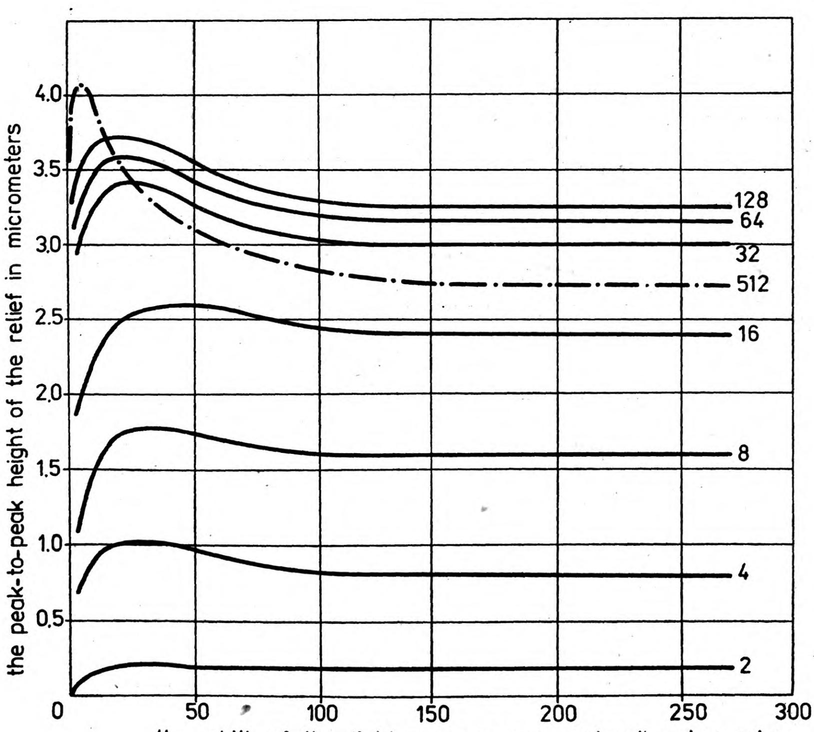

Fig. 5. The peak-to-peak height of the relief vs. the width of the light pulse at the exposure time as a parameter

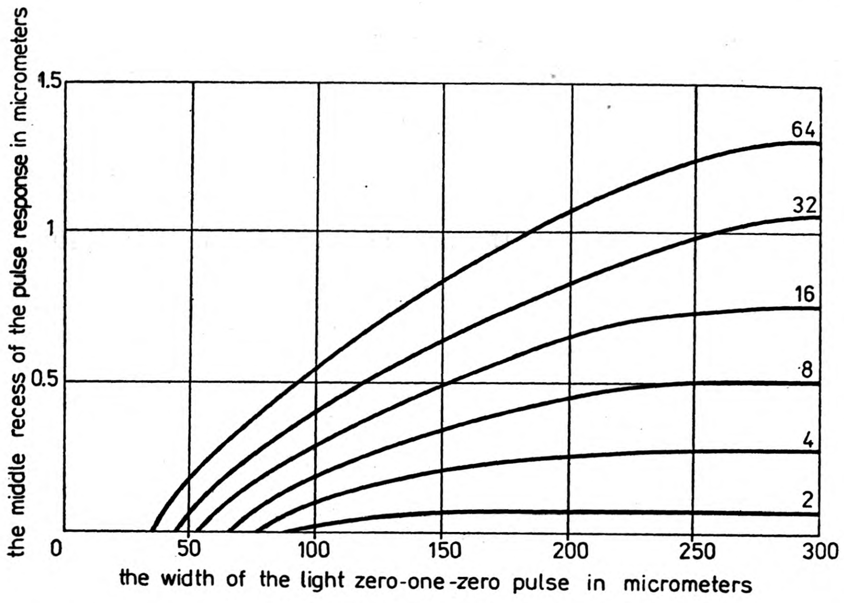

Fig. 6. The middle recess of the pulse response vs. the width of the light pulse at the exposure time as a parameter

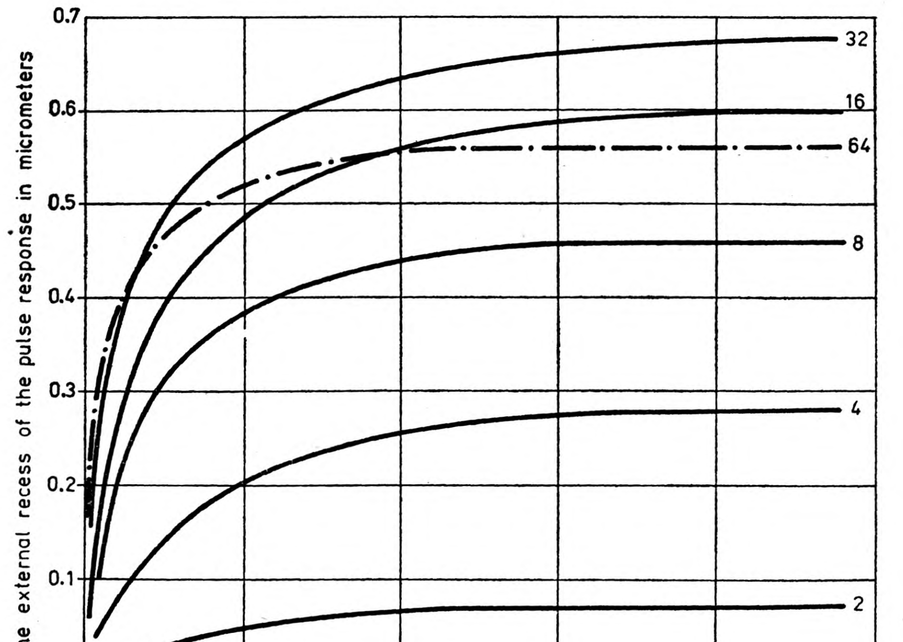

Fig. 7. The external recess of the pulse response vs. the width of the light pulse at the exposure time as a parameter

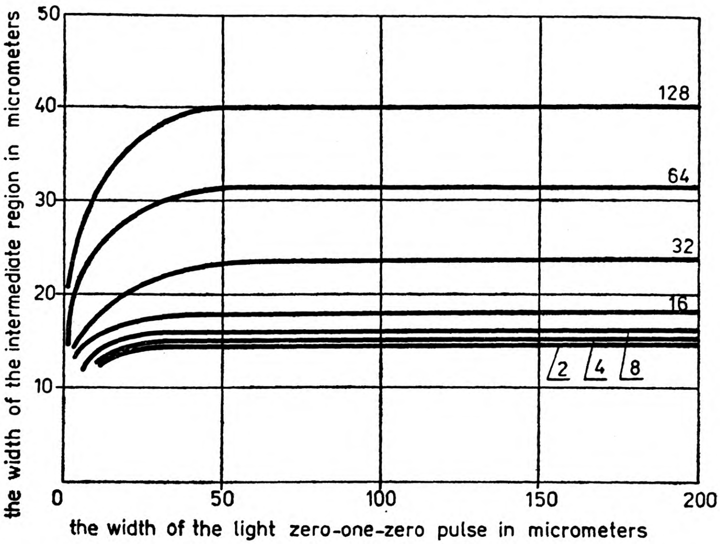

Fig. 8. The width of the intermediate region vs. the width of the light pulse at the exposure time as a parameters

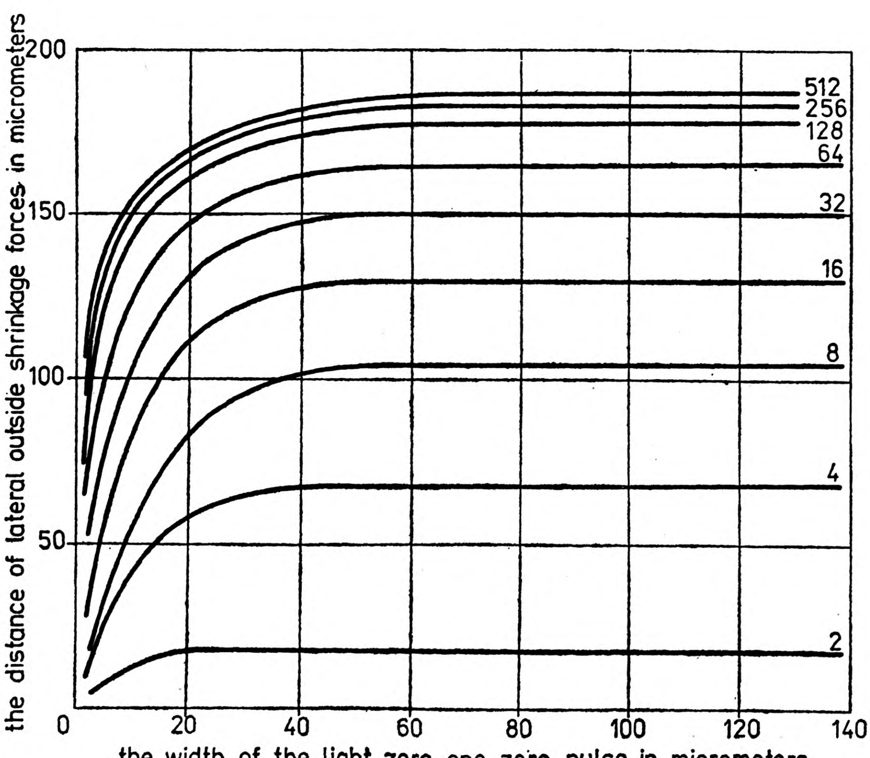

Fig. 9. The distance of the lateral shrinkage forces vs. the width of the light pulse at the exposure time as a parameter

From every exposure at least ten microinterferograms were photographically recorded for different widths of the light pulses. From every record the values of all the parameters listed above were determined. The final results in form of diagrams are presented in figs. 5–9, with the exposure time taken as a parameter.

4. Conclusions

As can be seen from the achieved results, the relief effects arising in photosensitive materials are nonlinear. Although the results presented in figs. 5–9 are related to relief effects arising in Kodak 649F plates, but appropriate conclusions may be deduced for other emulsion. If we look at the third interferogram in fig. 3, which corresponds to the light pulse width equal to 30μm, then we can notice that when the width of the light pulse is nearly double, compared to the emulsion thickness, the relief shape corresponds quite exactly to the light pulse shape. This may be treated as a suggestion as to the proper choice of the relation between the width of elementary lines composing the object recorded and the emulsion thickness.

References

[1] SMITH H. M., J. Opt. Soc. Am. **58** (1968), 533–539.
[2] LAMBERTS R. L., Appl. Opt. **11** (1972), 33–41.

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Функция расплывчатости в рельефных фотографических изображениях

Представлены результаты опытных исследований, касающихся образования рельефных изображений в эмульсиях типа Kodak 649 F. Исследовалась рельефная реакуция на световые импульсы с различной пространственной шириной и различной плотностью энергии. Опытным путём было выявлено, что вызывающие увеличение высоты рельефа боковые усадочные эффекты выступают в тех областях эмульсии, в которых градиенты оптической плотности отличныотнуля. Выявлено, что форма импульса рельефа наилучше отображает форму светового импульса, если длительность светового импульса приблизительно в два раза больше толщины эмульсии.