A SIMILARITY CRITERION IN THE OPTICS OF TURBID MEDIA

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Abstract

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A SIMILARITY CRITERION IN THE OPTICS OF TURBID MEDIA

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One of the most important optical characteristics of a turbid medium is its specific scattering χ ([1]), i.e., the ratio of the scattering coefficient to the total coefficient of absorption and scattering. It enters into all the fundamental equations of the optics of turbid media; that is, in essence, χ has long tacitly been regarded as a similarity criterion for optical fields in media with identical scattering indicatrices. However, for the first time, so far as we know, this quantity was called a similarity criterion in hydrooptics by V. N. Pelevin ([2]). In doing so, the author assumed that the scattering indicatrices of different water masses are identical. No experimental checks of the criterion χ were given in the cited work.

In order to confirm experimentally that in media with identical scattering indicatrices the criterion of similarity of optical fields is the specific scattering of the medium, we carried out the following experiments.

Milky, tinted and untinted media with known χ were illuminated by a vertical light flux from a projector (the divergence angle of the light flux about 5°, the diameter of the light field 50 cm). The absorption and scattering coefficients of the media were varied (while χ remained constant), and each time the brightness was measured in different directions at different depths. The receiver was a photometer with a field of view of 3°.3; the measuring instrument was an N359 self-recording direct-current milliammeter. The results obtained are shown in Fig. 1 for three values of χ. Along the abscissa is plotted the optical depth, and along the ordinate the relative brightness (the maximum brightness for each direction was taken as unity). The experimental points, with sufficient accuracy, lie near the averaged curves, although the magnitudes of the absorption and scattering coefficients varied by more than a factor of 4. It follows from this that, in these media, the brightness in identical directions at identical optical depths is the same. The same applies to the degree of polarization and to the position of the plane of polarization. From Fig. 1 it is also seen that, when χ decreases (i.e., when the fraction of absorption in the total attenuation of light increases), the brightness maxima in all directions approach the surface of the medium. Although the data presented do not describe completely the structure of the

Fig. 1. Distribution over optical depths τ of brightness in various directions in media with varying absorption and scattering coefficients, but with constant χ, for three values of χ (the criterion T is respectively equal to 0.04, 0.25, and 0.67; parameter ρ is about 0.23).

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light field in the medium, they are nevertheless already sufficient to show that in media with identical χ the optical fields are similar. Thus, the experimental data presented show that the specific scattering of a medium is a similarity criterion in media with the same scattering indicatrix, but not in media with different scattering indicatrices. In connection with this, the principal aim of the present work is to find a similarity criterion more universal than χ, one suitable for media with any scattering indicatrix.

Let us recall ([3]) that the brightness in the direction toward the light source decreases in a turbid medium down to a certain depth according to an exponential law with attenuation coefficient k; then the attenuation of light slows down (the transition region), and, finally, the light is again attenuated according to an exponential law, but now with attenuation exponent k' (the so-called coef-

coefficient of attenuation of the limiting diffusely scattered light). Simple considerations show that in optically similar media the brightnesses in the indicated (zero) direction at the same optical depth will be equal if the ratios k'/k in the media are the same (independently of the value of χ and of the form of the scattering indicatrix). Consequently, this ratio is a "criterion" of similarity, at least for the zero direction. But,

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possibly this ratio is the sought similarity criterion for the entire light field? Let us recall that the ratio $k'/k = T$ is a function of the parameter χ and of the quantity ρ, which is connected with the scattering indicatrix ([1,4,5]). In (1) a simple approximate analytical relation between these quantities was found,

$$T = \sqrt{\rho^{\chi}(1-\chi)^{\chi}}. \tag{1}$$

In the particular case when the parameter ρ is the same in the media, T depends only on χ, and thus T, like χ, is a similarity criterion for media with the same scattering indicatrix. In the more general case the quantity T, as is evident from (1), is also a function of ρ.

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

On the basis of the considerations set forth, we have made the assumption that **the parameter T is a similarity criterion for optical fields in any turbid media** (of course, for monochromatic light). We shall test this assumption experimentally.

Fig. 2. Distribution, over optical depths τ, of brightness in different directions in media with different χ and different ρ, but with the same criterion T, for two values of T. The smallest values of χ and ρ are respectively 0.56 and 0.2, and the largest 0.97 and 1.8.

Figure 2 gives the results of experiments analogous to those described, but carried out in media with different scattering indicatrices (in milk media, in rosin media, and in media prepared on the basis of Qualitex). In the rosin media and in the Qualitex media, in which χ depends strongly on wavelength, the measurements were made with a green filter. As can be seen, in media with the same T (but with different χ and ρ) the brightness in different directions at equal optical depths is practically the same, despite the fact that the measurements were made in such different media as milk and rosin.

Figure 3 plots the parameter T along the abscissa, and along the ordinate the optical depth found from the corresponding curves of the type in Fig. 1. The different points denote the optical depths of the brightness maxima in the given direction, obtained in four media with different scattering indicatrices. As can be seen, unlike Fig. 2, where the agreement of the points is very good, in Fig. 3 there is some scatter among them. However, all the points (both for the milk medium and for the rosin medium, etc.) lie near the averaged curve with more or less the same degree of accuracy. The scatter of the points is explained by the low accuracy of the experiment: nonuniformity over the cross section of the light field and insufficient sensitivity of the measuring apparatus introduced an error into the value of the relative brightness and, consequently, into the value of τ. Instability (for example, coagu-

Fig. 3. Variation of the optical depth τ of the brightness maxima in two directions as a function of the value of the criterion T

resin media affected the measurements of k and k'. Curves of the type shown in Fig. 3 were obtained for scattering angles varying from 5 to 90°. As examples, only two curves are given (for $\varphi = 30°$ and $\varphi = 50°$), from which it follows that, with increasing T, i.e., with increasing absorption in the total attenuation of light, the brightness maxima approach the surface, and the more slowly the

Fig. 4

Figure 4: Fig. 4

greater the absorption. This is in full agreement with the theoretical conclusions of L. M. Romanova [5]. The displacement of the brightness maxima toward the surface of the medium is also seen in Fig. 1.

Fig. 4. Dependence of the optical depth of the brightness maxima on the scattering angle in media with different values of the criterion T

From the averaged curves of the type shown in Fig. 3, Fig. 4 was constructed; along the abscissa axis are plotted the scattering angles, and along the ordinate axis—the optical depths of the brightness maxima in the corresponding directions. The numbers by the curves denote the values of the criterion T (in units of 0.1). In the case of a purely scattering medium ($T = 0$), the curve was obtained by extrapolating curves of the type shown in Fig. 3. Extrapolation of this curve toward $\varphi = 0°$ gives, as was to be expected [1], the value $\tau = 1$. With increasing T, the angle at which τ is maximal decreases.

Analyzing the presented series of experiments, taking into account the comparatively large scatter of points, we arrive at the conclusion that the experimental data, in any case, do not contradict the previously expressed assumption that T is a similarity criterion for optical fields in media with any scattering indicatrix. The criterion T, besides universality, has one more advantage in comparison with χ, namely the simplicity of its determination in practice. The point is that determining χ in turbid media is rather complicated. The efforts of many researchers were required in order, on the one hand, to find the fundamental possibilities for separate determination of the absorption and scattering coefficients needed to determine χ, and, on the other hand, to develop the simplest and most convenient practical (for example, at sea) methods of such determination. Much has already been done in this direction, but sufficiently accurate, convenient, and simple methods for determining χ still do not exist. To compute the criterion T, however, it is necessary to measure only two quantities: the extinction coefficient (by ordinary photometry in the laboratory or with a transparency meter at sea) and the attenuation coefficient of ultimately scattered light (measurement of the latter presents no fundamental or practical difficulties).

In conclusion, we note that in the future it is necessary to refine the limits of applicability of the criterion T, in particular, for media with absorbing particles.

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Note: Figure translations are in progress. See original paper for figures.