THE STRUCTURE OF A DIFFRACTED BOUNDARY "WAVE" ORIGINATING FROM A RESTRICTED BEAM

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The structure of a Young—Rubinowicz boundary "wave" formed by restricted beam edge diffraction is analyzed using the rigorous theory of diffraction. The meaning of the degeneracy of the amplitude break of this "wave" simulated by a computer in an edge dislocation is explained. The requirements supposing the identification of extended flanks of a boundary "wave" with real waves of an electromagnetic field are improved.

Introduction

As is known, the rim of a lighted screen appears to shine when observed from the shadow area [1]. Based on this observation, Young (1801) related the diffraction phenomenon to the rise of a wave diverging from the edge. Young designated this wave as *boundary wave* because its maximum intensity extends along the boundary of a geometric shadow. According to Young's model, the field observed behind the screen represents a superposition of two waves: a boundary wave and a residue of the initial wave passed by the screen. However, 15 years later, this model was displaced by the Huygens—Fresnel concept of secondary waves, which is more convenient mathematically. Afterwards, this model was the basis for Kirchhoff's diffraction theory.

Renewed interest in the boundary wave arose after the rigorous solution by Sommerfeld in 1896 of the problem of plane-wave diffraction by a perfectly conducting half-plane [1—3], and the mathematical substantiation by Rubinowicz in 1917 of the two-wave representation of a spherical wave diffracted by a round hole [1, 4, 5]. In both cases, it was possible to reduce the field behind the screen to a combination of two Young's components, but this was achieved by introducing a constant break in the boundary wave amplitude along the border of a geometric shadow [1—3, 6]. Since the independent existence of such a wave in free space contradicts the wave equation, and the hypothesis about the concentrated origin of its energy does not withstand elementary critiques, we shall henceforth use quotation marks at the use of the term boundary "wave".

However, the legitimacy of a critical estimation of the considered model appears doubtful due to reports of experimental observations of the boundary "wave", which have become especially frequent with the development of laser-based investigations [6—13]. Among the early results of this kind, Kalashnikov's report [7] merits notice, which has demonstrated the existence of divergent shadows from parallel needles illuminated with the light coming from a diffraction edge. Among modern reports, the most known is Ganci's experiment [11, 14] on the two-slit interference of a cylindrical wave that is divergent from edges, which clearly demonstrates the π phase-jump coincident with the boundary of a geometric shadow.

The rising validity of a boundary "wave" was promoted to a considerable degree by the appearance of fundamental theoretical works by Wolf and co-authors that offered a vector generalization of the "Rubinowicz representation" for waves with an arbitrary spatial distribution [15, 16]. Nevertheless, the discord between the experimental results mentioned above and the conclusions of the rigorous theory demonstrates the need to more adequately confront and define the significance of some theoretical background that is usually accepted only as a mathematical formalism.

In particular, our interest was a consequence of the deviation from such an immutable requirement of Sommerfeld's problem as the unbounded character of a diffracting plane wave. In the present research work, we attempted to develop an alternate version of the numerical analysis of the boundary "wave" structure formed by edge diffraction of the restricted beam.

1. Representation of an Integral Field by the Sum of Young's Components

To solve the problem of a plane wave diffracted by an infinite conducting half-plane (Fig. 1), Sommerfeld used

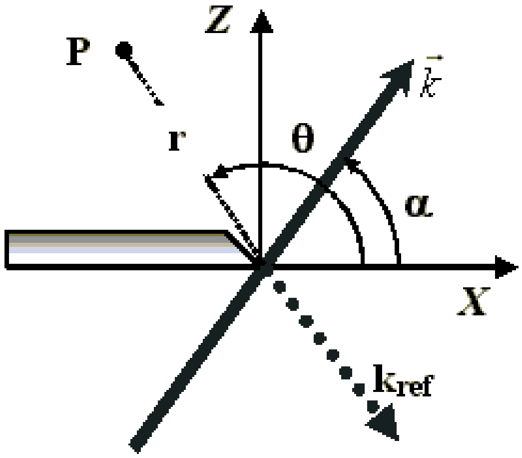

Fig. 1. Diagram of the plane wave or beam diffraction by the edge of a half-plane. In case of the beam, the quantity $\vec{k}$ is the wave vector of an arbitrary plane wave component

Helmholtz's equation, where u can represent either the electrical or magnetic field intensity, depending on polarization of the falling wave:

$$\Delta u + k^2 u + 0, \tag{1}$$

where $\Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}$. The corresponding edge requirements are either $u = 0$ for the case of E-polarization of a falling wave (Dirichlet), or $\frac{\partial u}{\partial n} = 0$ for the case of H-polarization (n — two-sided normal to a half-plane, Neumann). In both cases, there is also the requirement that $\lim\limits_{r\to\infty} r\left(\frac{\partial u}{\partial r} - iku\right) \to 0$ for radiation at infinity. The solution obtained by Sommerfeld for the case of E-polarization of a falling wave, upon breakdown into its Young's components is

$$u(P) = u_+^{(g)} + u_+^{(b)} - u_-^{(g)} - u_-^{(b)}, \tag{2}$$

where the first two terms represent the field spreading in the forward direction, and two last terms are responsible for the mirror-reflection wave [1—3]. It must be noted that the transition from E- to H-polarization of a falling wave leads only to sign alternation in the last two terms in (2), which corresponds to a reflected wave.

The first and third items in (2) describe the fields of geometric optics representing, respectively, the screen-transmitted and screen-reflected parts of an initial plane wave. In particular, the geometry-optical forward component can be expressed as

$$u_+^{(g)}\ (\mathrm{P}) = A_o \Phi(\alpha - \theta) e^{-ikr\cos(\theta - \alpha)}, \tag{3}$$

where A_0 is the amplitude of the initial wave; $\Phi(\alpha - \theta)$ is the Heaviside unitary function; the sense of quantities r, θ and α follows from Fig. 1; and $k = 2\pi/\lambda$ is the wave number. The second and fourth terms in (2) represent Young's boundary waves, the first of which propagates in a forward direction and is expressed as:

$$u_+^{(b)}(P) = A_o \left(\frac{1-i}{\sqrt{2\pi}} F(U) - \frac{\mathrm{sign}(\alpha - \theta)}{2} \right) e^{-ikr\cos(\theta - \alpha)}. \tag{4}$$

Here $F(U)$ is Fresnel's integral in complex form (5), where the upper limit expressed in terms of the coordinates in Fig. 1 is given by (6):

$$F(U) = \int_0^U e^{i\mu^2} d\mu, \tag{5}$$

$$U = \sqrt{2kr} \sin \frac{\alpha - \theta}{2}. \tag{6}$$

Because the most interest usually concerns the field diffracted in the forward direction, a subsequent attention will be focused on this field. As shown by the analysis, the presence behind the screen of fields from reflected components $u_-(P)$ becomes negligible at distances from the screen larger than a few tens of wavelengths [17]. In this case at sufficient distances from the screen, two last items in expression (1) may be neglected without loss of accuracy:

$$u_+(P) = u_+^{(g)} + u_+^{(b)}. \tag{7}$$

In this case, the general pattern of the field formed behind the screen is well known (Fig. 2,a). The amplitude distribution of this field on opposite sides of the shadow boundary is qualitatively different: the amplitude oscillations fade to a constant level in the open area of space, while the amplitude promptly and monotonically falls to zero in the shadow area. The result of formal partition of this field on the Young's wave components (3) and (1) is illustrated in Fig. 2,b and c, where the distribution of the modulus of their amplitudes is presented (the negative sign of the amplitude in Fig. 2,c corresponds to the π-jump in the phase of the boundary "wave"). Coincident components of both distributions are marked with an identical manner in Fig. 2,a and c.

As shown in the figure, the amplitude of each component undergoes a break at the edge of a geometric shadow, and, in addition, the boundary wave has a break in the amplitude derivative as well as a fracture of the wave-front. From Maxwell's theory, it is known that the self-maintained existence of fields with a break in the force lines in free space is impossible. Direct substitution of expression (3) into (1) provides evidence of the simulated character of such a field dissection and its contradiction to the wave equation. The observed luminescence of the screen edge in a shadow area is actually related to the existence behind the screen of the pair of physically valid waves with cylindrical structure of their common front [18].

2. Diffraction of the Restricted Beam

Let us return to Sommerfeld's problem (Fig. 1), having exchanged the falling homogeneous plane wave by a restricted beam. If the beam is represented by a superposition of plane waves with different angular orientations, then the diffraction of each of them can be viewed separately. In this situation, the final result should summarize all nascent Young's field components: the geometry-optical components and the boundary "waves" originating from each of the partial plane waves. As a result, the diffraction field of the beam can be expressed by the sum of pairs of terms that combine the similar Young's components of opposite direction.

We would recognize that the forced dissection of the diffracted field as a whole into two Young's components according to the Sommerfeld's example is problematic, because it demands a skewed circumcision of each of the partial plane waves with a fracture of the wave vector. In this situation, it is more logical to understand the integrated boundary "wave" as just a superposition of partial boundary "waves", i.e., the sum of all cylindrical field components with a geometric center on the edge of the screen. The second Young's component results from the combination of all the remaining geometry-optical components of the common field.

In practice, it is more convenient to treat the problem using Cartesian coordinates, where $r = \sqrt{x^2+z^2}$, $\alpha = \arccos(k_x/k)$, k_x is the projection of the wave vector k on the X-axis, and $\theta = a\cos(x/r) = a\cos(x/[x^2+z^2]^{1/2})$. The signum function $\mathrm{sign}(\alpha-\theta)$ shall be designated by

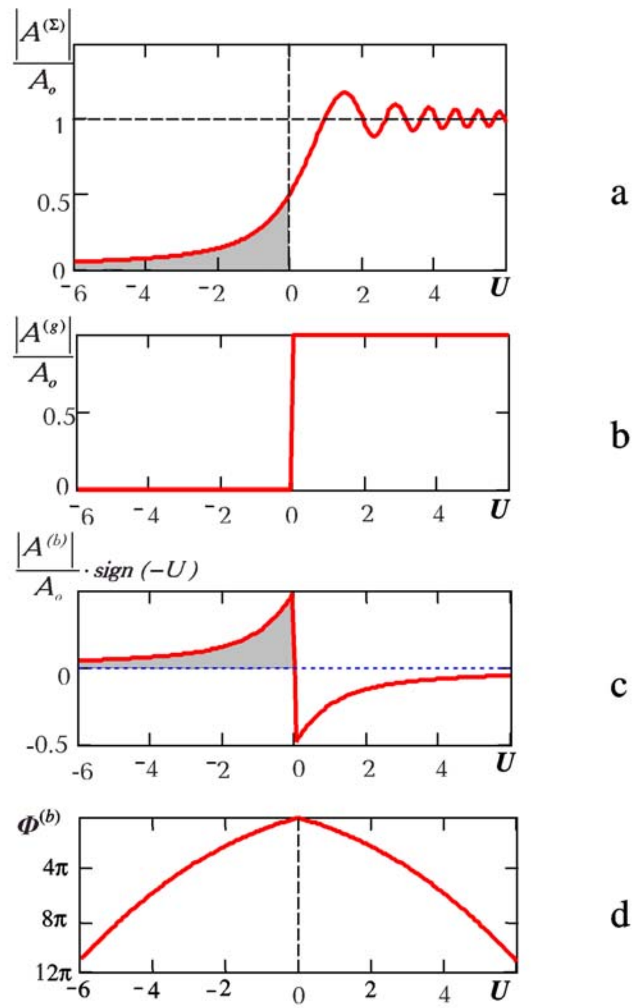

Fig. 2. Distribution of the integral field amplitude (a), geometry-optical component (b), boundary wave (c), and also phase of the boundary wave (d) in the region of the shadow boundary according to the rigorous Sommerfeld's solution. The central π-jump of the phase in Fig. 2,d is taken into account by the amplitude's variation in sign in Fig. 2,c

σ, and the unitary Heaviside's function $\Phi(\alpha-\theta)$ by h:

$$\sigma = \mathrm{sign}\left\{\arccos(k_x/k) - \arccos(x/[x^2+z^2]^{1/2})\right\}, \quad (8)$$

$$h = \Phi\left\{\arccos(k_x/k) - \arccos(x/[x^2+z^2]^{1/2})\right\}. \quad (9)$$

Equation (6) can be expressed in the Cartesian coordinates as

$$U = \sigma[k\sqrt{x^2+z^2} - k_x x - \sqrt{k^2-k_x^2}z]^{1/2}, \quad (10)$$

and the expressions for the geometry-optical components (2) and the boundary wave (3) are accordingly transformed to

$$u_+^{(g)} = hA_0 e^{i\left(k_x x + z\sqrt{k^2 - k_x^2}\right)} \quad (11)$$

and

$$u_+^{(b)} = A_0\left(\frac{1-i}{\sqrt{2\pi}}F(U) - \frac{\sigma}{2}\right) e^{i\left(k_x x + z\sqrt{k^2-k_x^2}\right)}. \quad (12)$$

Under the conditions that concern us, the rigorous solution for a field diffracted in the forward direction represents the compression of the Fourier-spectrum of the falling beam $f_G(k_x)$ with the solution for a single plane wave (6). Taking into account all the above statements, it can be written[1] in the form of

$$u^{(\Sigma)} = A_0 \int\limits_{-\infty}^{\infty} f_{\mathrm{G}}(k_x)\left\{h + \frac{1-i}{\sqrt{2\pi}}F(U) - \frac{\sigma}{2}\right\} \times$$

$$\times e^{i(k_x x + z\sqrt{k^2-k_x^2})}\, dk_x. \quad (13)$$

Furthermore, it is necessary to specify the type of a diffracting beam. Following the geometry of the problem, we shall restrict the plane wave amplitude to a two-dimensional Gaussian profile with an axis passing through the edge of a half-plane and oriented, for simplicity, perpendicularly to the edge:

$$B_{\mathrm{G}}(x,z) = \exp\left(-\frac{(x)^2}{w^2}\right) \times \exp(ikz), \quad (14)$$

where w is the radius of the beam corresponding to an amplitude of $1/e$ of the maximum. As is known, the free distribution of such a beam is accompanied by its automatic transformation to the Gaussian type (for example, [19]). The Fourier-spectrum of this beam is given by the formula

$$f_{\mathrm{G}}(k_x) = C_1 w \exp\left(-\frac{k_x^2\, w^2}{4}\right), \quad (15)$$

where C_1 is the normalization constant established by an inverse transformation of the spectrum $f_G(k_x)$ in an initial beam. In our case, its value amounts to $C_1 = 0.282$. Since the Gaussian distribution width of $2w$ can be arbitrarily large, it is possible to interpret the observed version of the edge diffraction as Sommerfeld's problem with a partially restricted plane wave.

Unfortunately, the immediate numerical calculation of the solution given by (13) is problematic because its core contains a complex Fresnel integral $F(U)$. Therefore, to progress further, we have used a simpler analytical representation of the complex amplitude of the boundary wave (12), which is given by:

$$A_+^{(b)} = \frac{1-i}{\sqrt{2\pi}}F(U) - \frac{\sigma}{2} \approx -\frac{\sigma}{2}\times$$

$$\times\left\{\frac{(1+i)\exp(iU^2)}{|U|\sqrt{2\pi} + \exp\left(-|U|^{1.04}\right) + i[1+0.4U^2]^{-0.6}}\right\}, \quad (16)$$

where the modulus difference from the original does not exceed 0.1 % and the phase difference does not exceed 0.6 % over the defined limits of the Fresnel integral ($-\infty < U < +\infty$) [20]. In order to compare the Young's components under investigation with their classical analogs (Figs. 2,*b*, *c*), the calculation of terms (13) corresponding to each of these components is carried out separately using the following formulas:

$$u_+^{(G)} = 0.282w \int\limits_{-k}^{k} h e^{i\left(k_x x + z\sqrt{k^2-k_x^2}\right) - \frac{k_x^2 w^2}{4}} dk_x, \quad (17)$$

$$u_+^{(B)} = -0.282w \int\limits_{-k}^{k} \frac{\sigma}{2}\times$$

$$\times\left\{\frac{(1+i)\exp(iU^2)}{|U|\sqrt{2\pi} + \exp(-|U|^{1.04}) + i[1+0.4U^2]^{-0.6}}\right\}\times$$

$$\times e^{i\left(k_x x + z\sqrt{k^2-k_x^2}\right) - \frac{k_x^2 w^2}{4}} dk_x. \quad (18)$$

The results of calculations of the structure of both components and of the integral field that combines them at different distances from the screen are shown in Figs. 3—6.

Evidently, at the initial moment, i.e., in the $z = 0$ plane, both Young's components are characterized by a former break in the amplitude. The jump of the latter is especially distinct for a geometry-optical component, whose clearly graduated profile near the shadow boundary (Fig. 4,*a*) remains at any magnification of the image scale. At the same time, at any small deviation from the screen plane, this leap is

[1] Present in curly brackets (13), the combination of step-functions h and $\sigma/2$ will result in a stationary value: $h - \sigma/2 \equiv 1/2$, which corresponds to the amplitude of the plane wave spreading in the same direction as the initial wave. Taking this circumstance into account, the integral field (6) is easily represented as a collection of the other couple of waves, which are free from amplitude ruptures and consequently more convenient for their theoretical and experimental modeling [17].

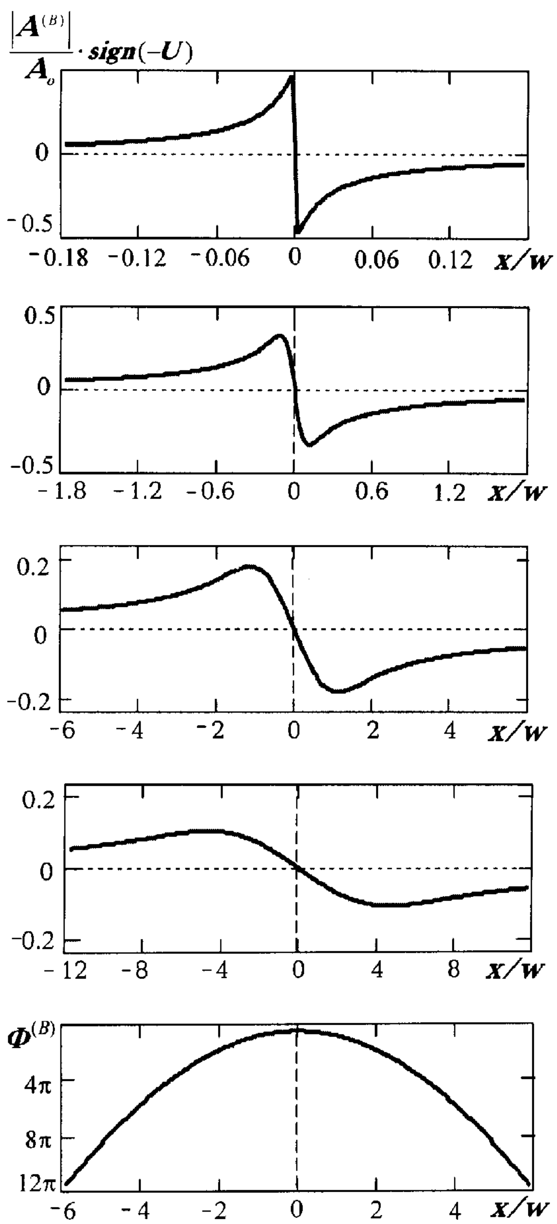

Fig. 3. Evolution of the amplitude distribution of an integral boundary wave at increasing distances from the screen (a—d) and the phase structure of this wave (e): a) $z = 10\lambda$; b) $z = L_R/10$; c) $z = L_R$; d) $5z = 5L_R$; e) $z = L_R$

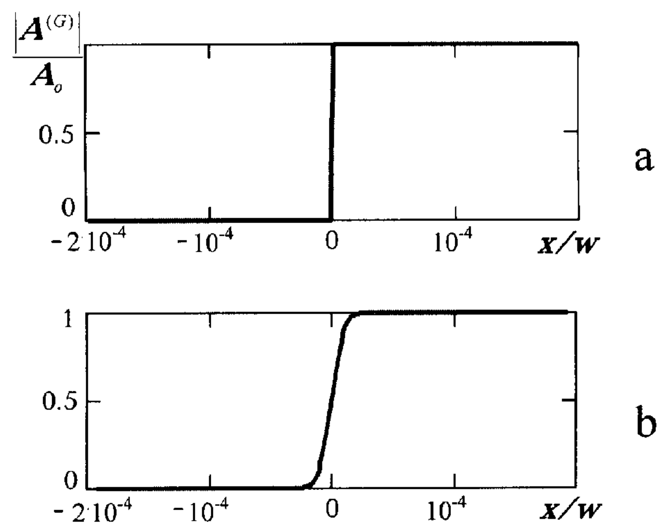

Fig. 4. Smoothing of the amplitude break of the integral geometry-optical component: a) $z = 0$; b) $z = \lambda/10$

transformed to an analytically smoothed transition from one amplitude level to another (Fig. 4,b), where the scale of the transition region increases according to the distance from the screen. The mentioned transformation is accompanied by the general smoothing of non-uniformity of an initial field distribution of the boundary "wave" with a relative increase of the amplitude of its flanks.

The disappearance of the wave-front break of the boundary "wave" (Fig. 3,e), which represents an analytically smooth cylindrical surface in neglect of a half-wave displacement on the shadow boundary, attests to the qualitative change of the situation. The structure and the geometry-optical components (Fig. 5) can be similarly transformed. Its initial asymmetry gradually decreases, becoming negligibly small at a distance from the screen of about the Rayleigh's length ($L_R = \pi w^2/\lambda$), and the general profile becomes more similar to the profile of the initial beam.

The integral field in the $z \leq L_R$ region has similar details of the classical distribution corresponding to the plane wave, but the average level for amplitude oscillations is now a negative-going beam profile (Fig. 6,a—c). As the distance from the screen increases, the evolution of the profile is determined by three basic processes: general field smearing, increasing the scale of amplitude oscillations, and their displacement from the shadow boundary with simultaneous fading in the region corresponding to the edge of geometry-optical component. The last circumstance leads to a consecutive deliverance of the distribution from the last extremes of oscillatory structure. As a result, by exceeding the Fresnel's diffraction region ($z \approx L_R$), the diffracted beam appears completely free from the previously mentioned oscillations, having now a smooth and distinctly asymmetric Gaussian profile with wide flat wings (Fig. 6,d). Its subsequent distribution leads

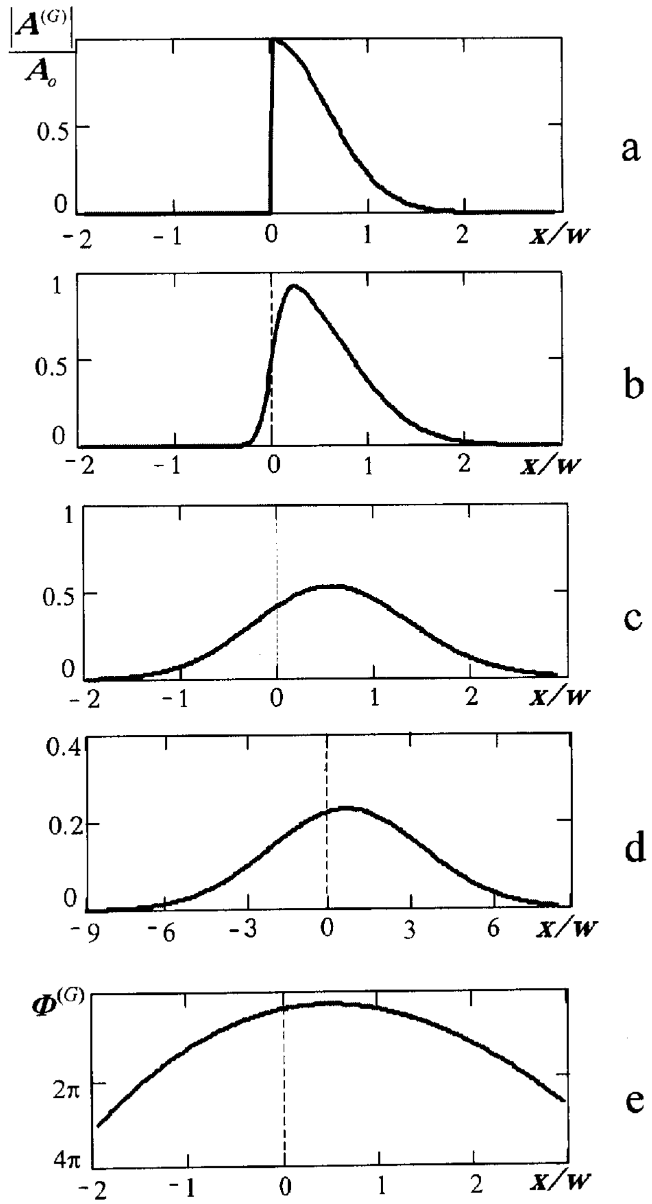

Fig. 5. The same, as in Fig. 3, for the integral geometry-optical components

only to the more complete symmetry of this distribution (Fig. 6,*e*).

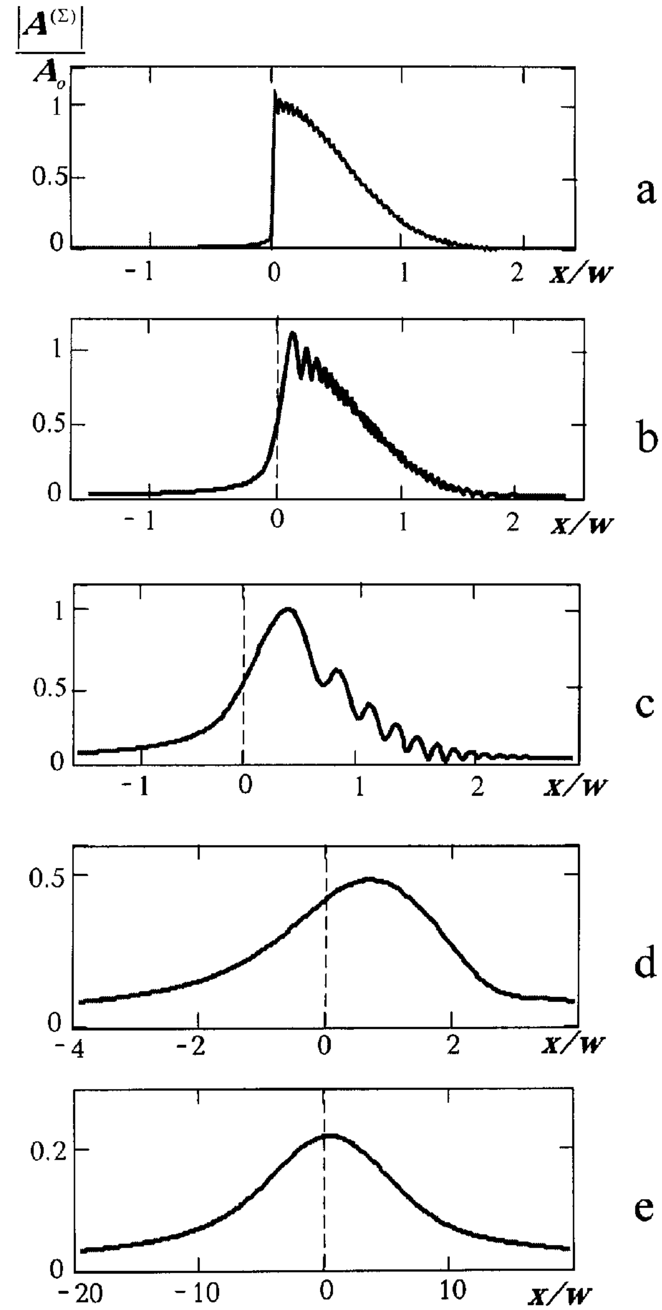

Fig. 6. Evolution of the amplitude distribution of an integral field of diffraction at increasing distances from the screen: a) $z = 10\lambda$; b) $z = L_R/100$; c) $z = L_R\ /10$; d) $z = L_R$; e) $z = 5L_R$

3. Discussion of the Results

At first glance, the most essential results of the research work is that it is necessary to attribute the transformation of the amplitude break of the boundary "wave" to the edge dislocation[2] of its front (Fig. 3), as the well as the transmutation of the geometry-optical component to a complete wave beam (Fig. 5).

[2]The common feature of the edge dislocation there is the transition of the field amplitude through the zero value with a simultaneous phase jump of this field equal to π [21]

Unfortunately, there is no prospect in proposing such a fundamental modification of the field structure under the conditions involved: the observed "regeneration" of both the Young's components is only a mathematical effect demonstrating the natural result of compression of both graduated and smooth functions. Really, the linear superposition of physically unreal waves, apparently, cannot generate a real wave. For example, it is simple to show the contradiction of the calculated integral components to the wave equation by means of the direct substitution of the expression for the field geometry-optical components (17) into (1) (where $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}$ with transition to Cartesian axes).

In fact, only the superposition of these components is physically real (Fig. 6). As stated before, the amplitude of their general field in the Fresnel's diffraction region ($z < L_R$) is characterized by oscillations whose magnitude and position change as the screen is moved further away, when their quantity sequentially decreases. The last effect becomes clear when taking into account that the scaling process of the described structure with the distance and the beam natural spreading happen with different velocities, the first process being much faster. Just as in Sommerfeld's problem, it is convenient to explain the observed modulation by interference between the boundary "wave" and the geometry-optical component. It clearly explains the disappearance of oscillations near the edge of the geometry-optical component, as well as the reason for their absence on the flanks of the distribution, where the field of the described component practically does not penetrate.

We next move on to the most relevant result of our calculation that qualitatively distinguishes it from the Sommerfeld's solution. It is easy to see (Figs. 3 and 5) that the spatial swing of the boundary "wave" originated by the beam noticeably exceeds the swing of the geometry-optical component, furthermore, this difference will increase as the screen moves further away. As a result, the overlapping region of both components appears localized in the central part of the resulting distribution, whose extended flanks represent nothing more than freely spreading wings of the boundary "wave".

Since the case in point is really the observed field, there is no obstacle to examine these flanks as independent cylindrical waves supporting the precise quantitative description. Essentially, it is in this sense that the actual content of the numerous reports about experimental observation and isolation of the boundary "wave" should be interpreted. The physical convention introduced by that (perceived or unconsciously) wave admission is compensated by the simplicity and obviousness of the Young model. That is important, for example, in the operative analysis of complicated situations. Let us define the quantitative boundaries for application of this model by basing them on the results of the rigorous diffraction theory.

As Sommerfeld noted, only at asymptotic examination when $r \gg \lambda$ [3] does the boundary "wave" acquire the character of a cylindrical wave radiated by the screen edge. In truth, the analysis of the rigorous solution shows that the situation is more complicated near the screen edge: the position of a geometric center for any local fragment of this "wave" does not coincide with the edge, but is displaced towards the falling wave. If Kalashnikov could arrange needles at the distance of a few wavelengths from the edge in his experiment [7], he would detect by the pattern of shadows that the source of the examined wave is transformed in this case into the chain of axes parallel to the edge, each of which is the center of its own cylindrical wave.

Thus, the asymptotic requirement mentioned above

$$r \gg \lambda \qquad (19)$$

can serve as a specific quantitative criterion which restricts the area of a Young model application below. To satisfy this requirement, it suffices to move a few tens of wavelengths away from the edges of the screen, which is usually realized in optical experiments with a margin.

Less obviously, there is the concretization of the requirement that eliminates the area of space, where the physical separation of the Young's components is impossible, from examination. In this case, we have to take into account the fact that, for plane wave diffraction, it is only possible to affect the partial angular separation of the two components, while, for beam diffraction, it is only possible to affect the partial spatial separation. The general condition can be formulated as follows: the Young's model is usable only in the absence of both spatial and angular overlapping of the boundary "wave" and geometry-optical component.

For a formal declaration of this requirement, we shall take the concept of a light flux "volume" the defined as the multiplication of its transverse section with an angular divergence: $\Delta X\, \Delta\theta$ (for example, [19]). Then the validity criterion of the examined model can be written as

$$x^{(B)}\theta^{(B)} \notin (\Delta X)_{\min}\, (\Delta\theta)_{\min}, \qquad (20)$$

where $x^{(B)}$ and $\theta^{(B)}$ are arbitrary crossing and angular coordinates of the boundary "wave", and $(\Delta X)_{\min}$ and

$(\Delta\theta)_{\min}$ are the least of the two Young's components by values of transverse section and angular divergence. It is easy to note that, for plane wave diffraction {when $u^{(g)}(\theta) = \delta(\alpha - \theta)$}, requirement (20) does not consider the boundary of the geometric shadow, and, for beam diffraction, it does not consider the region of mutual overlapping of the Young's components.

The final restriction is stipulated by localization of the boundary "wave" flanks on different sides from the boundary of the shadow, which was already eliminated above from examination. Therefore, each of these flanks can be described by a Young's model as independent cylindrical waves:

$$u_{+}^{(B)}(U) = \begin{cases} u_1^{(B)} & \text{при } U < 0; \\ u_2^{(B)} & \text{при } U > 0. \end{cases} \tag{21}$$

Therefore, the list of the most essential physical inaccuracies of the examined model displayed by the rigorous Sommerfeld's solution is exhausted. Any problem concerning edge diffraction that fulfils requirements (19)—(21) can be resolved exactly by use of Young's concept. This explains the reason for the unfailing trust in this model in practice, which until now remains almost as popular as the venerable Kirchhoff's theory.

Conclusion

The preceding analysis of the boundary "wave" structure formed by the edge diffraction of a restricted beam allows us to estimate the objective possibilities of Young's model. If the requirements mentioned previously are met, this model provides not only a physically plausible, but also a mathematically precise pattern of the field formed behind the screen. Nevertheless, its application remains noticeably restricted. The problem is caused by excessive simplification and contradiction to the rigorous theory of the wave treatment of the diffraction process. This circumstance becomes especially relevant to apertures having shapes more complicated than rectilinear, which evidently are the most interesting. The physically unrealizable waves involved in the analysis of the field in this case can only confuse the real view of the process that takes place.

Experience shows that another approach is considerably more reliable for such an analysis, whereby the rigorous Sommerfeld's solution is reduced to an analogous number of physically irreproachable waves which exist in full correspondence with requirements of electrodynamics and wave optics [17]. The transition to such waves considerably simplifies the calculation, interpretation, and experimental modelling of any fields that are formed under the diffraction of arbitrary waves by arbitrary apertures [22]. The problem considered in the present report is no exception, where the same resulting field with cylindrical shaped wavefronts can easily be represented as a superposition of the appropriate waves.

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СТРУКТУРА ДИФРАГОВАНОЇ МЕЖОВОЇ "ХВИЛІ", ЯКА ПОРОДЖУЄТЬСЯ ОБМЕЖЕНИМ ПРОМЕНЕМ

С.П. Анохов, А.І. Хижняк, Р.А. Лимаренко

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З використанням строгої теорії дифракції аналізується структура межової "хвилі" Юнга—Рубіновича, що народжується при крайовій дифракції обмеженого променя. Пояснено справжній зміст змодельованого комп'ютером перенародження амплітудного розриву цієї "хвилі" в крайову дислокацію. Уточнено умови, що допускають ототожнення протяжних флангів межової "хвилі" з реальними хвилями електромагнітного поля.