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国际声学工程与技术学术会议论文集

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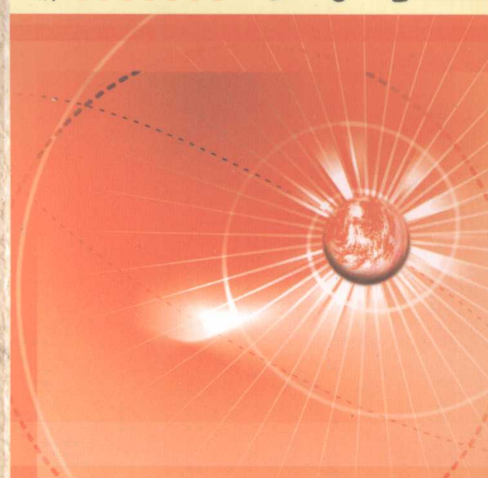

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内容简介

本书收集了声学工程与技术方面具有较高学术价值的一些优秀论文，主要内容包括相关的理论，模拟实验，建模和实际生产设计中的相关研究，具有较强的理论水平，有助于解决许多工程中的实际问题。

本书可为相关行业的学者和科学技术人员借鉴和参考。

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CONTENT

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Anomalous Phenomena at Propagation of Sound Waves Near the Sea Bottom

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Abstract A review is presented of numerous experimental data that exhibit anomalies in sound transmission through the water-sand interface of the sea bottom at overcritical angles of incidence. These data are complemented with those of in-sea experiments performed with a side-scan sonar for low grazing angles. It is shown that the explanations given by different researchers for the anomalous phenomena are insufficient, and a development of a new theoretical model is required to allow for all aspects of the problem.

In applied acoustics, a class of problems exists whose solutions are based on that of a simpler classical problem of sound reflection and refraction at an inter- face between two media. Such problems sprimarily include the problems of sound propagation in a waveguide [1], where the phenomenon of total internal reflection plays a key role.

Muir, Horton, and Thomson [2], 1979, were the first to express doubts about the validity or at least about the completeness of the classical theory for describing the reflection and refraction processes. Their paper considers an experiment on the reflection and refraction at the interface between water and sand at a sea bottom for bounded beams generated by a parametric sound source. The authors argued that the experimental data agree well with the theory only for undercritical angles of incidence. For overcritical angles, the experiment led to anomalous results, namely:

- the amplitude of the transmitted wave was by 10-15 dB higher than the calculated one (the amplitude anomaly);
- the sound field in the refracted wave was spread over a wide angular range (the anomaly of the refraction angle).

The aforementioned paper gave rise to a number of publications and discussions in which mainly experts in parametric sound sources participated. The conclusion of the discussion was summarized by Williams and Satkoviak [3] in 1989, who attributed the amplitude anomaly to the specificity of calculating the performance of the parametric projector. In their opinion, even in the far-field zone, the sound field of the parametric source retains its sensitivity to the structure of the transverse aperture factor, which is governed by the distribution of the boundary function at the pump projector; when this factor is appropriately chosen, the theory can be corrected and brought into agreement with the experiment. However, even the corrected theory lacks in explaining the anomaly of the refraction angle.

The conclusions formulated in [3] seemed to be unconvincing for Chotiros [4], whose paper appeared in the same year and caused a new wave of publications and discussions. In his paper, Chotiros both confirmed the anomalous results of the previous studies [2] and obtained the frequency dependence for the observed phenomena. By using linear but well directed sound sources, Chotiros nearly excluded the errors in the theoretically estimated signal level of the transmitted wave and, respectively, in the anomaly of the level.

The experiments of Chotiros were performed in a shallow-water sea with sandy bottom, with a technique that was thereafter repeatedly used by other researchers. According to this technique, the transmitted waves were received by a system of hydrophones distributed along orthogonal axes of a cubic array. The vertically distributed hydrophones served to analyze the vertical structure of the transmitted wave, while the hydrophones distributed over the three axes of the array were used to determine the relative time delays and the propagation direction for the transmitted wave. The sound beam was generated by a source that was at a distance of 4.5 m from the bottom surface. The angular position of the tower-mounted projector relative to the receiving array could be changed so that the grazing angle of the incident wave took the values 90°, 59°, 39°, 29°, and 22°.

The amplitude anomaly, i.e., the offset of the measured amplitude from the calculated value, along with its frequency dependence, is illustrated by Fig.1a taken from [4], where the tower positions *3* and *5* correspond to undercritical and overcritical incidence angles, respectively (the corresponding grazing angles are 39° and 22°). At the frequency band $f = (5–80)$ kHz, the estimated amplitude anomaly is $A = (0\text{-}60)$ dB, while $A = (10\text{-}15)$ dB at $f = 20$ kHz, which agrees with the estimate of [2].

Figure 1b [4] illustrates the anomaly of the refraction angle. Here, the frequency dependences are presented for the apparent and effective sound speeds in the bottom material, which are calculated in accordance with the Snell law from the refraction angle, sound speed in water, and incidence angle specified by the experimental layout. In the model represe4ntation, the sandy bottom itself is treated as an equivalent fluid. For tower positions *1-3* that correspond to undercritical incidence angles, the experimental sound speed in the sea floor agrees well with the model one, while, in position *5,* which corresponds to overcritical angles, the effective sound speed decreases from the expected value C = 1742 m/s to 1100-1000 m/s at higher frequencies of the band $f = (5–80)$ kHz.

Among the later publications of Chotiros [5-8], paper [6] should be mentioned on detecting the low-velocity wave component in the field of the transmitted waves.

In this work, a technique was proposed that was subsequently used by other experimenters. According to this technique, the experiment was carried out in a hydroacoustic tank whose bottom was covered with sand, which was prepared in a specific manner to get minimal surface roughness. A bottom-moored vertical chain of hydrophones was used for the signal reception. An omnidirectional source of pulsed sound signals could horizontally move at a distance of 0.5 m from the bottom. From the measured amplitude and arrival time of the pulsed signal, the parameters of transmission were obtained and compared with the calculations. The calculated dependences of the arrival times were plotted for both refracted and diffracted components [1] of the transmitted signal, with the sound speeds C = 1742 m/s and C = 1200 m/s in the bottom material, on the assumption that the Snell law was valid at the interface.

These experiments clearly showed that the signal arrival times satisfactorily corresponded to the calculated sound speed, C = 1742 m/s, for the undercritical incidence angles (curves *a* and *b)*. However, as the horizontal distance and incidence angle increase, the arrival time consistently shifts to the plot (curve c) that corresponds to the speed C = 1200 m/s in the bottom material, thereby exhibiting the anomaly of propagation velocity (Fig.1c [4]).

The same technique was used in [8] to measure the angular distribution of acoustic intensity in the transmitted wave. According to these measurements, the maximum of the angular distribution changes in accordance with the Snell law at undercritical angles, as if the sound speed in the bottom material took the calculated value 1675 m/s. However, in the domain of critical angles, another peak appears in the angular distribution that remains predominant as the grazing angle decreases down to 9.7°. This peak corresponds well to sound speeds of 1100-1200 m/s in the bottom material, and the angle of anomalous refraction is 45°-55° (Fig. 2 [8]).

The anomalies of the refraction angle and propagation speeds were used by Chotiros to propose an explanation for the anomalous phenomena by applying the theory of sound propagation in two-phase media, which was earlier developed by Biot [9]. According to the Biot theory, three types of waves can exist in a two-phase medium like sea sand: two longitudinal waves and a shear wave. Among these waves, the second longitudinal one has an anomalously low velocity, $C_{L2}\approx$400m/s, and two other waves propagating with quite "normal" velocities, $C_{L2}\approx$(1700−1750) m/s and C_t=100m/s, which correspond to the experimental data. According to Chotiros, the second (slow) longitudinal wave is just what can be responsible for the anomaly of the refraction angle, because it implies no phenomenon of full internal reflection at all. However, to agree with the experimental data, this wave should have a velocity of 1000-1200 m/s. To come to the quantitative agreement, Chotiros varied the parameters of the two-phase medium of the sea-sand type to obtain a specific dispersion dependence for the velocity of the slow longitudinal wave. The resulting dispersion proved to be so strong that it yielded a value of about 400 m/s at low frequencies and the desired value 1000-1200 m/s at the experimental frequencies 5—60 kHz.

On the other hand, an alternative point of view appeared in recent years, and it was proposed in [14-21]. The proposed explanation is based on the well-known theory of sound difraction by the randomly rough surface of the sea bottom. This theory has been successfully used in [14-17] to explain the anomaly of the refraction angle and the apparent decrease in the effective sound speed in the bottom material. In [18], quantitative estimates are given for the amplitude anomaly and its dependence on the depth of the observation point, as related to the diffraction-caused insonification of the bottom halfspace. However, the unique experimental data obtained in [19-21] with the techniques earlier tested in a shallow sea and a hydroacoustic tank offers convincing evidence that the proposed explanation of the anomalous phenomena is at least not the only one.

The first example: Let us consider the aforementioned experimental data in more detail. In [19], an improved technique is reported for the measurements in a hydroacoustic tank whose bottom is covered with a layer of sea sand prepared in a specific manner. The surface of the sand was either smoothed to a condition of an even plane or brought to a condition of roughness. The measuring technique included variation of the horizontal position of the omnidirectional sound source at a distance of 0.5 m from the bottom and sequential changes in the depth of the receiving hydrophone within the bottom bulk down to a depth of 90 cm with a step of 1.5 cm. Upon processing the amplitude-phase information, the technique provides the cross sections of the sound field in the bottom, which take the form of wave fronts in the depth-distance coordinates. These fronts characterize the complex pattern of sound refraction and diffraction for the entire range of incidence angles, including the overcritical ones. Figures 3a and 3b illustrate the experimental pattern of the sound field for the smoothed surface, both at low and high frequencies (5 and 50 kHz, respectively).

At a frequency of 5 kHz, the sound field structure is represented by a set of quasi-spherical wave fronts, which corresponds to the refracted waves. The propagation velocity of the waves along the interface corresponds well to the water wave: there are no traces of the bottom (lateral) wave. The absence of any anomalies in the sound field structure at 5 kHz fully agrees with the earlier conclusions of Chotiros [4].

A quite different pattern of the sound field is observed at a frequency of 50 kHz, which is illustrated by Fig. 3b. Two subsystems of wave fronts are visible, one of which corresponds to the quasi-spherical (refracted) waves in the domain of undercritical angles and the other corresponds to a surface source located in the domain of overcritical incidence angles. The two subsystems interfere to produce a maximum in the sound pressure at the apparent refraction angles 45°-55°, the corresponding apparent sound speed in the bottom material being 1100-1200 m/s.

It is clear that these apparent values, although agreeing well with those observed in [4-8], have nothing in common neither with the slow wave predicted by the Biot theory nor with diffraction-type sound scattering by the bottom surface, which is treated as smooth in the case at hand. At the frequency 50 kHz, the sound field structure itself is anomalous in the sense that it does not follow the classical description [1].

The second example: The quantitative estimate C=1200 m/s for the effective velocity of the transmitted wave, at which the slow component manifests itself, is obtained on the assumption that the refraction mechanism acts and the Snell law is valid. If one supposes that the slow component is the surface wave with a synchronous excitation, the effective propagation velocity C = (1380−1420) m/s will correspond to the same delay times, the specific value of the velocity depending on the parameters of the sand. It is clear that, for a wave with such characteristics to exist, one needs either some other model for the bottom material which differs from that of Biot, or another mathematical model for the bottom halfspace which differs from the classical one.

Finally, the unique experimental data reported in [13], [18], and [20] complement the results reported in [4] on estimating the amplitude anomaly of the transmitted wave and its dependence on the parameters of the problem. These experiments were performed in the sea, with the use of a parametric projector and broadband (delta-like) pulses, for wide ranges of reception depths and grazing angles. The following conclusions can be drawn from the aforementioned publications:

- the amplitude anomaly grows as the reception depth increases and the grazing angle decreases;
- the amplitude anomaly exhibits an intricate interference-caused dependence on the frequency and grazing angle (see [18] and [20]) and on the reception depth [13];
- at the experimental frequencies 5-15 kHz, the amplitude anomaly is estimated as 30-80 dB at the low grazing angles 30°-15° (see [18] and [20]).

Note that, according to [4], the amplitude anomaly changes by 30-40 dB per decade within the frequency band 5-80 kHz when the reception horizon is fixed and the grazing angle is equal to 22°.

The undoubtedly unique estimates were obtained in [13] for the amplitude anomaly at a grazing angle of about 4.3°, with different reception depths. To simplify the analysis, we present these data in Fig. 4, with curve *1* corresponding to the calculated signal level in the inhomogeneous wave of the lower halfspace and curve 2 corresponding the experimental data given in [13]. It is evident that the amplitude anomaly exhibits an intricate interference-caused dependence on the reception depth, and the signal level reaches its maximum at some horizon under the surface. One can suppose that, at such small grazing angles, the decrease in the signal amplitude does not follow the exponential law in the near-bottom layer, as the model requires: it rather increases up to some horizon, remains inhomogeneous within the near-bottom layer, and spherically diverges outside this layer.

Let us consider the spectra of the received signals, which are shown in Fig. 5

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