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NONSPECULAR REFLECTION, RESONANCE SCATTERING, AND RADIATION OF SOUND BY ELASTIC BODIES IN WATER

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Results of studies of sound reflection by plates and shells immersed in water are given. The are incidence angles of sound waves upon plates or shells, under which strong reflection backwards, i.e. nonspecular reflection, is observed. Physical nature of nonspecular reflection is discussed and its theory is given. It is demonstrated that nonspecular reflection is accompanied by the effect of spatial-frequency resonance. It is revealed that resonance scattering and radiation of sound by shells immersed in water is connected with the effect of spatial frequency resonance. The discussed effects can play the dominant role in formation of underwater acoustic fields.

In the late 40s through the early 50s, systematic investigations of underwater sound reflection from ships and other objects were initiated. The experiments were carried out in the Black Sea under the supervision of Yu. M. Sukharevskii. Until 1957, I was his main assistant in these studies. Our experiments led us to the conclusion that the conventional representation of real objects as bodies characterized by total sound reflection was inexact. In reality, the objects under study were represented by elastic shells or structures consisting of plates and supplied with reinforcing ribs, frames, and stringers.

In 1951 Sukharevskii offered me the opportunity (I was his post-graduate student) to study the reflection of sound from submerged plates and shells. At that time, only a few publications on this subject could be found in the literature.

One of these publications attracted our attention [3]. It presented the results of experimental studies of sound reflection from a thin steel plate immersed in water. It was found that, at some large angles of incidence, the incident sound waves were strongly reflected backwards. Such reflection was called nonspecular, because it occurred at a nonnormal incidence of sound waves on the plate. The nonspecular reflection was associated with bending vibrations of the plate, but the physical mechanism of the nonspecular reflection remained unclear.

We performed detailed studies of sound reflection from submerged thin plates made of brass, steel, and aluminum. These experiments revealed a new type of nonspecular reflection due to transverse compressional vibrations (longitudinal vibrations) of the plates [4]. Later, we observed the nonspecular reflection of sound from bounded cylindrical and spherical shells. On the basis of the experimental studies, a theory of nonspecular sound reflection from plates and shells was developed. A new phenomenon was observed a spatial-frequency resonance due to the interaction of bounded plates and shells with the sound field in water. The notion of the length of the spatial relaxation to the natural vibrations of a submerged plate (shell) was introduced. Simple criteria were formulated that determined cases corresponding to different types of behavior for the submerged shells and plates types of behavior characteristic of bounded or unbounded objects. The results of these studies were described in early papers (see, e.g., [5-7]).

By analyzing the physical mechanism and the theory of the nonspecular sound reflection from plates and shells, we concluded that the nonspecular reflection occurred at the angles of incidence corresponding to the equality between the tangential phase velocity of the wave incident on the plate (or shell) and the velocity of the normal wave in the plate (or shell) immersed in liquid. Experiments with thin and thick rods (elastic cylinders) and thick plates confirmed this conclusion. We also observed nonspecular reflections caused by longitudinal and bending waves in thin rods, as well as by Lamb waves in thick plates and elastic cylinders [8-10].

It was found that the spatial-frequency resonance is responsible for the fine structure of the nonspecular reflection, as well as for the resonance scattering of sound waves from submerged shells (cylindrical or spherical) or other elastic bodies. The resonance scattering is observed also in the case of a sound wave incident on a cylindrical shell in the direction normal to its surface. This occurs if the frequency of one of the natural shell vibrations (modes) is equal to the frequency of the incident wave and the wavelength of the periphery waves forming the mode exceeds the wavelength of sound propagating in water at this resonance frequency. The notion of the length of the spatial relaxation to the natural vibrations of a plate or a shell was deduced from both physical concepts [5] and the rigorous theory of sound diffraction at the edge of a semi-infinite plate [11] or a semi-infinite cylindrical shell [12]. This notion proved to be significant for understanding the role of inhomogeneities, reinforcing ribs, stringers, and frames in the formation of the nonspecular reflection and scattering of sound. Indeed, if the size of the plate (shell) segment bounded by the reinforcing ribs is small compared to the length of the spatial relaxation, this plate segment will behave as a bounded object, which will result in an enhancement of nonspecular reflection.

The understanding of the fact that the nonspecular reflection is related to the excitation of a normal wave in the plate or shell allowed us to explain the role of the plate (shell) curvature in the formation of nonspecular reflection. In the case of a flat plate, the nonspecular reflection of sound is observed near two angles of incidence corresponding to the excitation of either longitudinal or bending vibrations (waves). If the plate is characterized by a nonzero curvature, the nonspecular reflection may occur also at some other angles of incidence, because, in such a plate, longitudinal and bending waves are possible that propagate with velocities different from (exceeding) those of longitudinal and bending waves in a flat plate.

The main result of the studies of nonspecular sound reflection from submerged plates and shells was the conclusion that in some practical cases, the reflection of sound waves from real objects can be nonspecular. This conclusion was especially important for low frequencies. At low frequencies, the nonspecular reflection and resonance scattering lead to a significant increase in the scattering cross-section of the object as compared to its so-called "geometrical" scattering cross-section. It is significant that, at low frequencies, the nonspecular reflection and resonance scattering cannot be eliminated by conventional passive methods of vibration damping, vibration absorption, and sound absorption. In the mid-50s, the studies of sound emission from submerged shells became highly topical. At that time, much of the physics of sound reflection from shells and plates was understood. An idea was put forward to apply the acoustic reciprocity principle to the problem of sound radiation from the shells in order to use the results obtained for sound reflection. However, it was found that, in acoustics, the reciprocity principle had no rigorous mathematical basis, although nearly a hundred years have elapsed since Helmholtz published his first paper on the reciprocity principle (1860), followed by Rayleigh's publications on that subject. A rigorous mathematical justification of the reciprocity principle was obtained on the basis of the theory of self-conjugate operators and Green's formula. This result was reported at the IV All-Union Conference on Acoustics in 1958 [13] and in [14]. In the latter, an integral reciprocal relation was obtained for the sound fields formed as a result of the radiation and diffraction of sound by a shell. From this relation, it followed that all effects observed for the sound reflection from submerged elastic bodies occur also in the sound fields formed as a result of sound radiation from plates and shells (for example, the spatial-frequency resonance and the presence of sound radiation maxima in the angular characteristic of the radiation field due to the normal waves or resonance radiation). This conclusion was verified by experiments [15].

Based on the integral reciprocal relation [14], we proposed a method for solving the boundary-value problems of sound radiation from plates, shells, and other elastic bodies [16]. These relation also underlied different new methods developed for describing acoustic radiation fields (see, e.g., [2,17,18]). The results obtained in [16] gained wide recognition in many countries. This paper was often cited along with the classic works of Helmholtz and Rayleigh (see, e.g., [2,17,18]).

As for the above-mentioned publications on the nonspecular sound reflection from plates and shells, they were probably somewhat ahead of their time. Some of the results reported in these papers were practically discovered anew thirty years later. For example, De Billy *et al.* [1] obtained exactly the same results as those reported in our publication [10] on the nonspecular sound reflection caused by Lamb waves in a submerged thick plate. Other examples of such publications also exist. This situation is quite natural since more than 30 years have passed.

Beginning in the 1960s, numerous papers and monographs were published on sound reflection and radiation from different kinds of shells [19,20]. A new direction of research was formed in underwater acoustics, i.e. the acoustics of shells.

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