self-noise of ships, submarines, and torpedoes: self-noise levels

Self-noise differs from radiated noise in that the measurement hydrophone is located on board the noise-making vessel and travels with it, instead of being fixed in the sea at a location some distance away. Although the fundamental causes of noise are the same, the relative importance of the various noise sources is different. Moreover, in self-noise, the paths by which the noise reaches the hydrophone are many and varied and play a dominant role in affecting the magnitude and kind of noise received by the hydrophone on the moving vessel.

In the sonar equations, radiated noise occurs as the parameter *source level* SL, where it is the level of the source of sound used by passive sonar systems. By contrast, self-noise is a particular kind of background noise occurring in sonars installed on a noisy vehicle; in the sonar equations, self-noise occurs quantitatively as the *noise level* NL. Self-noise exists in fixed hydrophones as well, whenever the manner of mounting or suspension creates noise of its own.

Self-noise is one of many different kinds of undesired sound in sonar and originates in a variety of ways. Figure 11.1 illustrates the interrelationships of the various kinds of sonar backgrounds. Self-noise refers to those noise sources between the dashed lines.

Self-noise depends greatly upon the directivity of the hydrophone, its mounting, and its location on the vehicle. On surface ships, the sonar transducer is located in a streamlined dome projecting below the keel of the ship. On older submarines, the principal passive

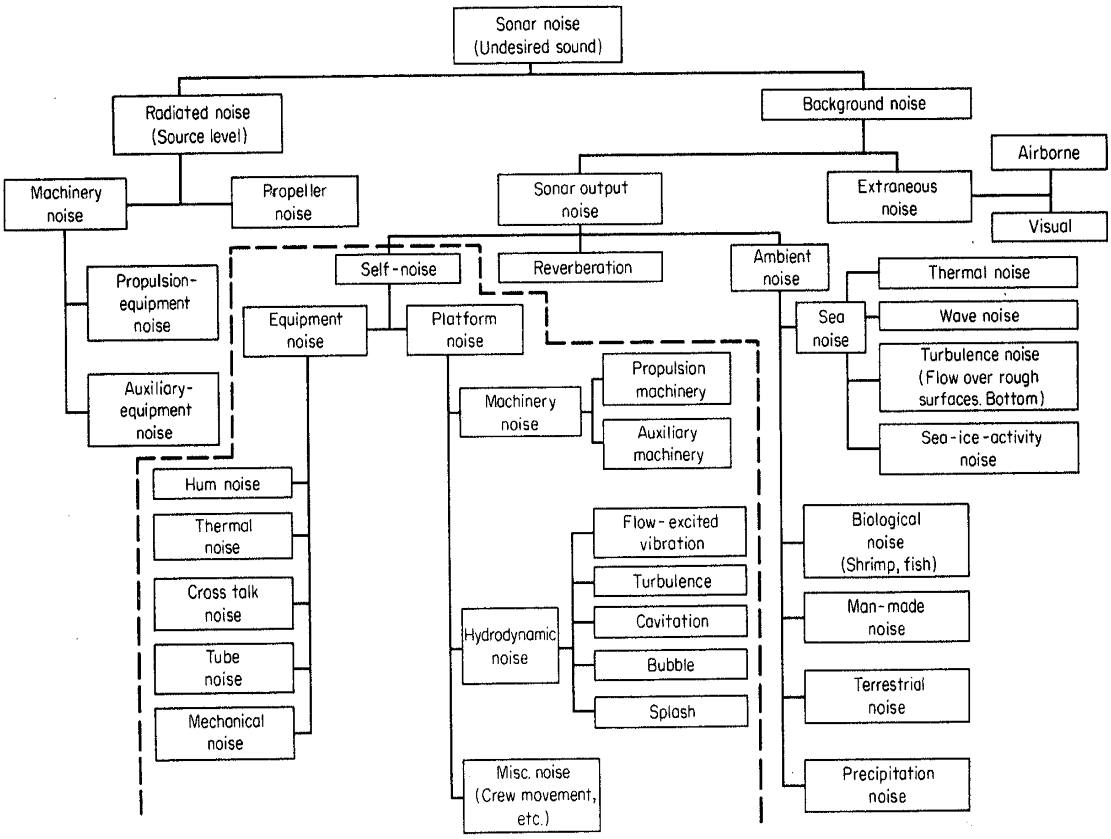


fig. 11.1 *Interrelationships of various sonar noise sources. (Ref. 1.)*

sonars were the JT and JP sonars, having horizontal line transducers placed topside toward the bow of the vessel; on modern submarines, a large portion of the bow of the vessel is taken over by the sonar transducer. Acoustic homing torpedoes often have their transducers in the nose of the torpedo and face forward in the direction of travel. On all these vessels, the sonar transducer is placed as far forward on the vessel as is practicable, so as to be removed as much as possible from the propulsion machinery and the propeller noises of the vessel. Figure 11.2 is a pictorial view of the location of the sonar transducer on these three kinds of vessels.

11.1 Self-Noise Measurements and Reduction

Self-noise measurements on these vehicles have been made in the past with sonar hydrophones of varying sizes and shapes and hence of differing directivity. In order to make these various measurements compatible with one another, and at the same time make them useful for other directional sonars, it is convenient to express self-noise levels as *equivalent isotropic levels*. The equivalent isotropic self-noise level is the level that would be indicated by a nondirectional hydrophone of sensitivity equal to that of the directional transducer with which the self-noise measurements were made. If the noise level measured with a directional hydrophone is NL′, the equivalent isotropic level is

$$\mathrm{NL} = \mathrm{NL}' + \mathrm{DI}$$

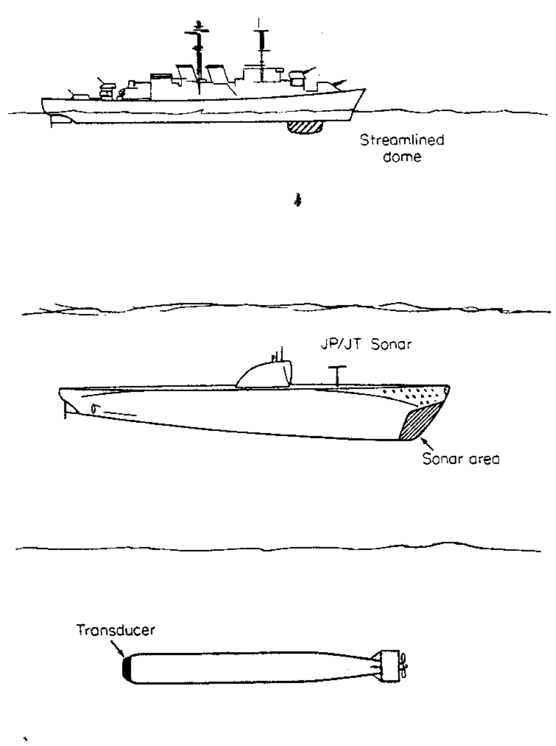


fig. 11.2 *Locations of the sonar transducer aboard surface ships, submarines, and torpedoes.*

In converting to equivalent isotropic levels, therefore, the measured levels NL′ are corrected for directivity by applying the directivity index of the measurement hydrophone. The isotropic level NL is the level required for use in the sonar equations previously written.

Although this convention serves to bring self-noise measurements made on the same kind of vessel with different transducers into some degree of agreement, some hesitancy must be felt when applying self-noise data obtained with one sonar to a sonar of different design, directivity, mounting, and location on the same vehicle. Self-noise, like ambient noise, is seldom isotropic in its directional and coherence characteristics, and the DI is not always a satisfactory measure of the discrimination of transducers against it. Often noise coming from a single direction will predominate, and the DI will be almost meaningless as a measure of the discrimination against noise. In torpedoes, for example, it has been found that the front-to-back ratio of the transducer beam pattern—defined as the difference in response between the forward and backward directions—is a more useful measure of the discrimination against self-noise than the directivity index. In general, it is necessary to understand the sources and paths of the prevailing kind of noise before transferring self-noise data from one sonar to another. When this knowledge is lacking, the equivalent isotropic self-noise level must be used in the sonar equations, with recognition of its crude nature and of the likelihood that large errors may occur in some circumstances.

11.2 Sources and Paths of Self-Noise

The three major classes of noise—*machinery noise, propeller noise,* and *hydrodynamic noise*—apply for self-noise as well as for radiated noise. The sound and vibration generated by each kind of noise reach the sonar hydrophone through a variety of different acoustic paths.

Figure 11.3 shows a surface ship and the paths in the ship and through the sea by which sound generated at the propeller and in the machinery spaces of the ship can reach the sonar hydrophone. Path *A* is an all-hull path by which the vibration produced by the machinery, the propeller shaft, and the propeller itself reach the vicinity of the sonar array at a forward location. Here it may be reradiated by the hull or, more importantly, cause vibration of the wall of the streamlined dome and the mounting of the hydrophone array. Path *B* is an all-water path leading directly from the ship's propellers to the hydrophone. Path *C* shows propeller noise backscattered by volume scatterers located in the volume of the sea. In general, these scatterers are the same as those causing volume reverberation. Path *D* is the bottom-reflected or scattered path by which propeller noise can reach the vicinity of the hydrophone. This path is likely to be a major contributor to self-noise on surface ships operating in shallow water.

For submarines and torpedoes, the upward analog of Path *D*—reflection and scattering from the sea surface—is, similarly, an important acoustic path

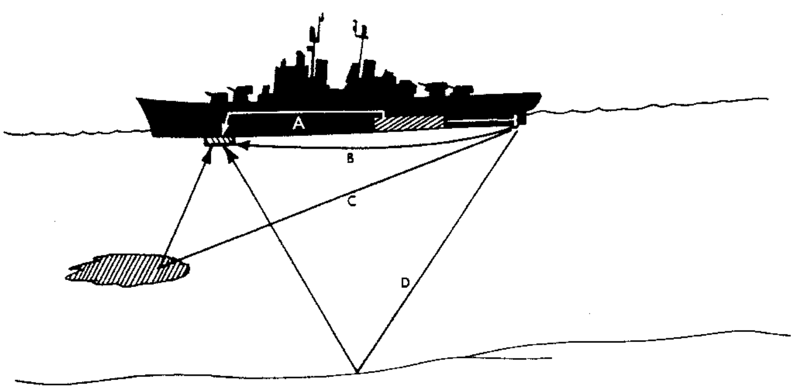


fig. 11.3 *Paths of self-noise on a surface ship.*

when the vehicle is running at a shallow depth. An example of this kind of path is shown in Fig. 11.4. This is an artist's conception of a torpedo with three areas of forward and side scattering on the surface by which sound from the propellers can reach hydrophones located near the nose. Of all the vessels of interest, the self-noise of torpedoes long ago received a considerable amount of analytical attention, probably because of the relative ease of performing experiments upon them. For example, torpedoes were "run" with and without propellers, in water and in air, and with various modifications, all during the World War II years (2).

Both machinery noise and propeller noise are prominent contributors to self-noise. The self-noise contribution of the vessel's machinery occurs principally at low frequencies as tonal components in the overall noise. Unlike other kinds of noise, machinery noise tends to be relatively independent of speed,

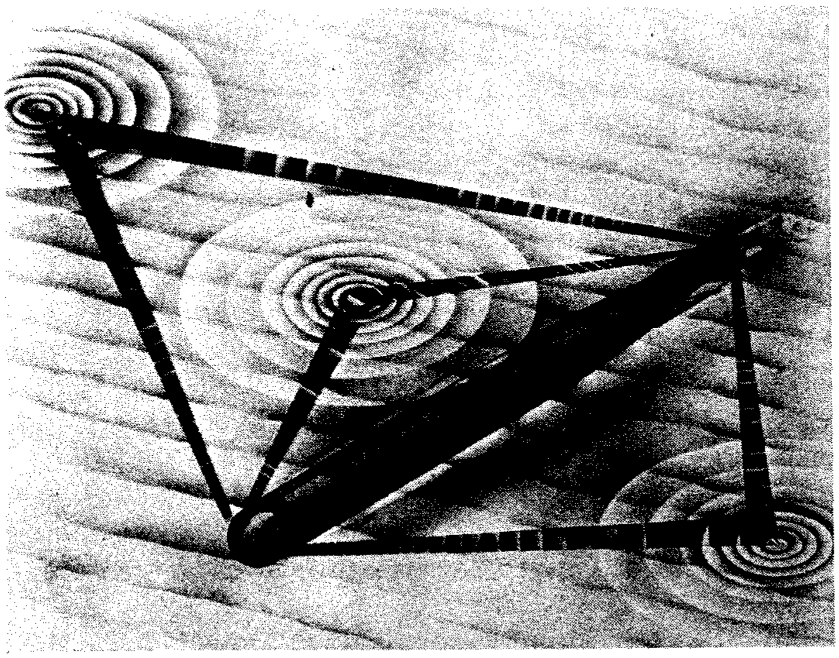


fig. 11.4 *Surface-reflected paths of torpedo self-noise.*

since much of it originates in the constant-speed auxiliary machinery of the vessel. Hence, at slow speeds, where other kinds of noise are of low level, the noise of the vessel's auxiliary machinery is often a troublesome source of self-noise. In the wartime JP equipment on submarines operating below 5 knots, it was observed that listening was affected by power operation of the bow and stern planes, the steering machinery, and certain rotating equipment aboard the submarine. At higher speeds, propeller noise becomes the dominant contributor to self-noise under conditions of high frequencies, shallow water depths, and stern bearings. At high speeds also, the many and diverse forms of hydrodynamic noise become important.

Hydrodynamic noise includes all those sources of noise resulting from the flow of water past the hydrophone and its support and the outer hull structure of the vessel. It includes the turbulent pressures produced upon the hydrophone face in the turbulent boundary layer of the flow (flow noise), rattles and vibration induced by the flow in the hull plating, cavitation around appendages, and the noise radiated to a distance by distant vortices in the flow. Hydrodynamic noise increases strongly with speed, and because the origin of this noise lies close to the hydrophone, it is the principal source of noise at high speeds whenever the noise of propeller cavitation—itself a form of hydrodynamic noise—is insignificant.

The relative importance of the sources of self-noise can be illustrated by showing their areas of dominance on a plot having vessel speed and frequency as the two coordinates (Fig. 11.5). At very low speeds, the hydrophone "sees" the ambient noise of the sea itself. With increasing speed, machinery noise tends to dominate the low-frequency end of the spectrum, and a combination of propeller and hydrodynamic noise becomes important at high frequencies. The scales and the crosshatched regions separating the noise sources in Fig. 11.5 vary with the kind of vessel and with the directivity, location, and mounting arrangement of the measuring hydrophone.

Hydrodynamic noise occurs in stationary hydrophones as well as in those on moving vessels. Around the case of an acoustic mine on a rocky bottom, for example, a swift tidal current was found (3) to produce pressures of 1,000

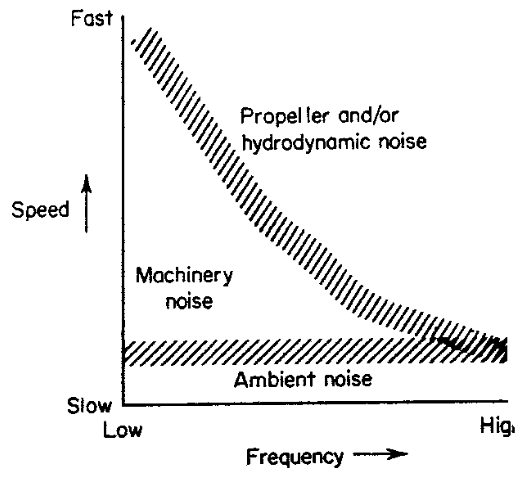


fig. 11.5 *Regions of dominance of the sources of self-noise.*

dyn/cm^2 in the 1- to 4-Hz band and 50 dyn/cm^2 in the 5- to 32-Hz band on the crystal hydrophone of the mine.

Electrical noise is occasionally bothersome in sonar sets as a form of self-noise. However, its existence indicates a pathological condition whose cure is normally obvious. Except under exceptionally quiet conditions, as at times in the Arctic under a uniform ice cover, electrical noise is not a serious problem in well-designed sonars.

11.3 Flow Noise

A particular kind of hydrodynamic noise has been called *flow noise.* Because it is amenable to theoretical and experimental study and has an urgent application to the reduction of cabin noise inside aircraft, it has received relatively abundant attention in the literature. Flow noise, in actual practice, may be said to be what is "left over" after all other sources of hydrodynamic noise aboard the vessel have been accounted for or removed.

Flow noise consists of the pressures impinging upon the hydrophone face created by turbulent flow in the turbulent boundary layer about the hydrophone. Figure 11.6 illustrates a rigid, flat boundary containing a flush-mounted pressure hydrophone, above which a viscous fluid is flowing. Between the free stream and the boundary lies a turbulent boundary layer within which fluctuating pressures are created and are transmitted to the hydrophone in the boundary. Although these turbulent pressures are not true sound, in that they are not propagated to a distance, they form what has been termed "pseudosound" (4) and give rise to a fluctuating noise voltage at the output of the pressure hydrophone. In the following sections, some of the salient characteristics of flow noise will be briefly summarized. The interested reader is referred to the quoted literature for more detailed information; a good tutorial paper on the subject has been published by Haddle and Skudrzyk (5).

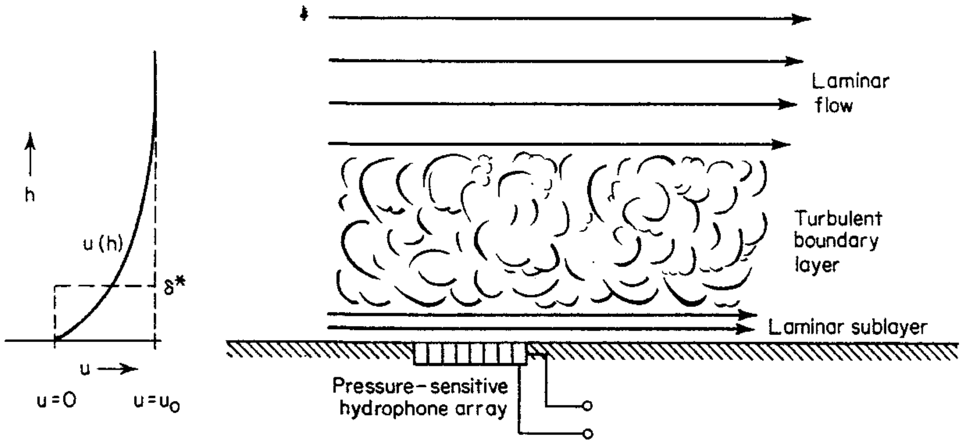


fig. 11.6 *Flow structure in a fluid moving over a stationary surface. The diagram at the left shows the variation of flow velocity with height above the boundary.*

Total fluctuating pressure The rms pressure p_{rms} on the boundary due to the turbulent flow is related to the free-stream dynamic pressure by

$$\frac{p_{rms}}{\frac{1}{2}\rho u_0^2} = 3 \times 10^{-3}\alpha$$

where ρ = fluid density
u_0 = free-stream flow velocity

α is a constant, called the Kraichman constant after a pioneering investigator of turbulent flow, ranging from 0.6 to 4 in different measurements using different data (6), but centering roughly about unity. In any one series of measurements, α is found to be a constant over a wide range of flow velocities.

Spectrum of flow noise The power spectrum of flow noise, or the distribution in frequency of the mean-squared pressure, is found to be flat at low frequencies and to slope strongly downward at high frequencies at the rate of f^{-3}, or as −9 dB/octave, as shown by the flow-noise spectra observed with a flush-mounted hydrophone ½ in. in diameter inside a rotating cylinder (6). The transition frequency f_0 between the flat and the sloping portions of the spectrum is given by

$$f_0 = \frac{u_0}{\delta}$$

where δ is the thickness of the boundary layer. Since the flow velocity is a continuous function of distance away from the wall (Fig. 11.6), the boundary-layer thickness is more exactly expressed by the "displacement thickness" δ^* such that

$$\delta^* u_0 = \int_0^\infty u(h)\, dh$$

where $u(h)$ is the flow velocity at a distance h normal to the wall. The actual boundary layer is thus replaced by an equivalent layer (in the above sense) of zero velocity (that is, the layer is attached to the wall) and of thickness δ^*. It is found that $\delta = 5\delta^*$, approximately. In experiments of Skudrzyk and Haddle (6), δ^* was found to be 0.153 in. at a speed u_0 of 20 ft/s and 0.135 in. at 60 ft/s.

Variation with speed At frequencies less than f_0, the spectrum level of flow noise varies as the cube of the speed u_0; at frequencies appreciably greater than f_0, it varies as the sixth power of the speed. The latter rate of increase amounts to 18 dB per speed doubled. This is equivalent to a straight-line rate-of-rise of 1.8 dB/knot in the speed range 10 to 20 knots, in approximate agreement with observations of self-noise on large naval surface ships over this range of speed.

A practical way to measure flow noise without the contaminating effects of machinery noise is to use a sinking streamlined body as a test vehicle or,

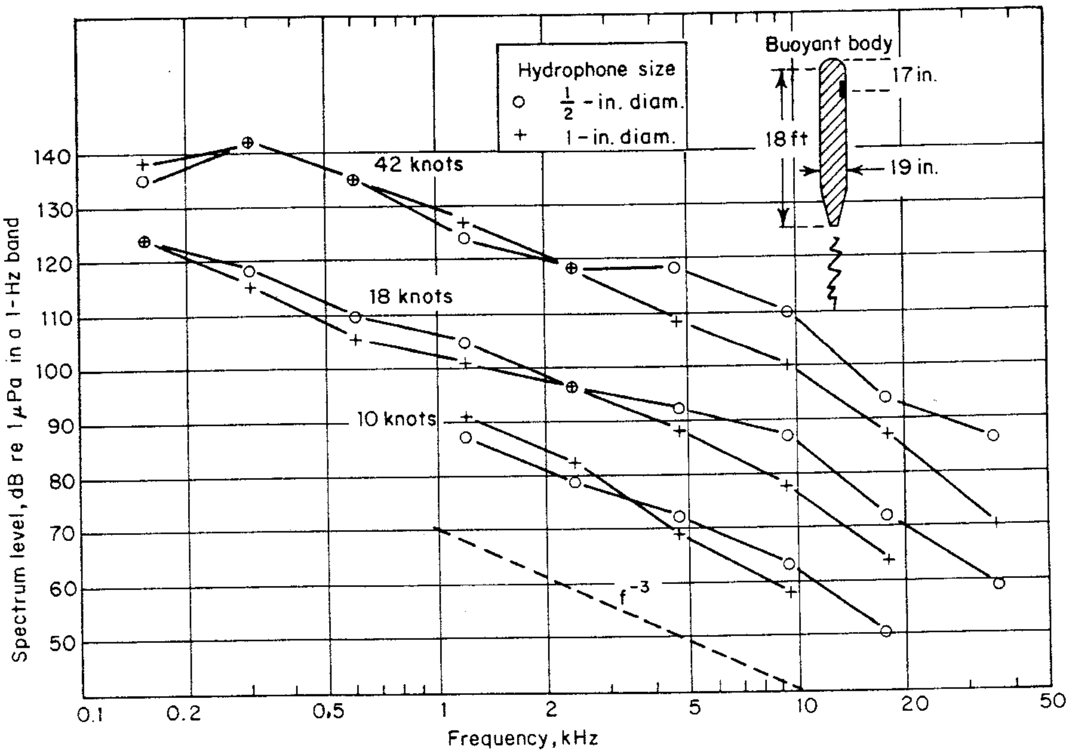


fig. 11.7 Flow-noise levels on a buoyant body at different speeds for two hydrophone diameters. (Ref. 5.)

alternatively, to use a buoyant body rising under its own buoyancy from a depth in the sea. Examples of measurements by Haddle and Skudrzyk (5) on a buoyant streamlined body are shown in Fig. 11.7. The data shown here were obtained with two hydrophones of different sizes placed 17 in. behind the nose of the body 18 ft long. The results roughly confirm the 18-dB increase per speed doubled just described, as well as the f^{-3} variation with frequency. It will be noted that doubling the hydrophone diameter from ½ to 1 in. *decreased* the flow-noise level by some 5 to 10 dB near the high-frequency end of the spectrum.

Effect of surface roughness Flow noise across a rough surface has been studied by Skudrzyk and Haddle (6) using a rotating cylinder having different degrees of surface roughness obtained by cementing grit of various sizes to the outside. It was found that at 24 kHz the noise produced by the roughnesses became equal to the flow noise across the perfectly smooth surface when the height of the roughness was such that

$$h = \frac{0.06}{u'}$$

where u' = flow velocity, knots
h = roughness height, in.

Surfaces need not be optically smooth to be considered "smooth" for flow noise, but must be free of roughnesses high enough to extend above the laminar boundary layer (Fig. 11.6) and affect the turbulent flow.

Coherence of turbulent pressures Measurements of the longitudinal and transverse correlation of the pressures due to the flow have been made with small hydrophones in the walls of tubes and pipes (7, 8). In a frequency band w hertz wide centered at frequency f, the crosscorrelation coefficient of the pressure measured at two points along the walls at distance d apart has been found (7) to be

$$\rho(d,w) = \rho(s)\frac{\sin(\pi w d/u_c)}{\pi w d/u_c}\cos 2\pi s$$

where s is the (nondimensional) Strouhal number defined as

$$s = \frac{fd}{u_c}$$

in which u_c is the "convection velocity" equal to the velocity at which turbulent patches are carried past the hydrophone by the flow. u_c is somewhat smaller than the free-stream velocity u_0 and varies from $0.6u_0$ to $1.0u_0$, depending on the frequency f. The correlation function $\rho(s)$ has been found experimentally to be

$$\rho_L(s) = e^{-0.7|s|}$$

for longitudinal separations d parallel to the flow (7), and

$$\rho_T(s) = e^{-5|s|}$$

for transverse separations at right angles to the flow (8).

Discrimination against flow noise A pressure hydrophone of finite size, that is, an array, will discriminate against flow noise to an extent determined by the spatial correlation coefficients ρ_L and ρ_T described above. The magnitude of this discrimination β is defined as

$$\beta = \frac{R'}{R}$$

where R' is the mean-square voltage output of an array placed in a flow noise field, and R is the mean-square voltage output of a very small pressure hydrophone placed in the same noise field and having a sensitivity equal to the plane-wave axial sensitivity of the array. The quantity 10 log $(1/\beta)$ is equivalent to the *array gain for flow noise;* the ratio β measures the reduction of flow noise experienced by an array of pressure-sensitive elements relative to the noise pickup of a single small element. The magnitude of the discrimination factor β has been worked out by Corcos (8) for circular and square arrays, on the assumption that the correlation function in oblique directions to the flow is given by the product of the two principal components ρ_L and ρ_T. White (9) has extended this work by means of a unified theory and has carried out computations for rectangular arrays with long side parallel to and perpendicular to the direction of flow. Figure 11.8 shows the quantity β as defined above for a rectangular array (after White) and for a circular array (after Corcos). For a large square hydrophone of side equal to L, Corcos shows that

$$\beta = \frac{0.659}{\gamma^2}$$

where $\gamma = 2\pi f L/u_c$, and for a circular hydrophone of radius r,

$$\beta = \frac{0.207}{\gamma^2}$$

where $\gamma = 2\pi f r/u_c$. In both cases, γ must be much greater than unity.

Comparison with an isotropic sound field If now we define a *convection wavelength* λ_c such that

$$\lambda_c = \frac{u_c}{f}$$

in analogy with acoustic wavelength

$$\lambda_s = \frac{c}{f}$$

where c is the velocity of sound, the expression for the discrimination factor of a circular hydrophone becomes

$$\beta = 0.207 \left(\frac{\lambda_c}{2\pi r}\right)^2$$

For isotropic noise, the corresponding expression is (Table 3.2)

$$\beta_{iso} = \left(\frac{\lambda_s}{2\pi r}\right)^2$$

where 10 log $(1/\beta_{iso})$ is the ordinary directivity index of the circular array. Comparing the two expressions, we observe that $\beta = 0.207\,\beta_{iso}$ *when the appropriate wavelength is used for the two types of noise*. But λ_c is far smaller than λ_s for vehicles traveling in the sea; the ratio λ_c/λ_s is approximately equal to the Mach number of the vessel, or the ratio of its speed to the speed of sound in the sea. Since M is a small quantity, it follows that the discrimination against flow noise for a large array of a given size is much greater than it is for isotropic noise. In terms of the Mach number M,

$$\frac{\beta}{\beta_{iso}} = 0.207M^2$$

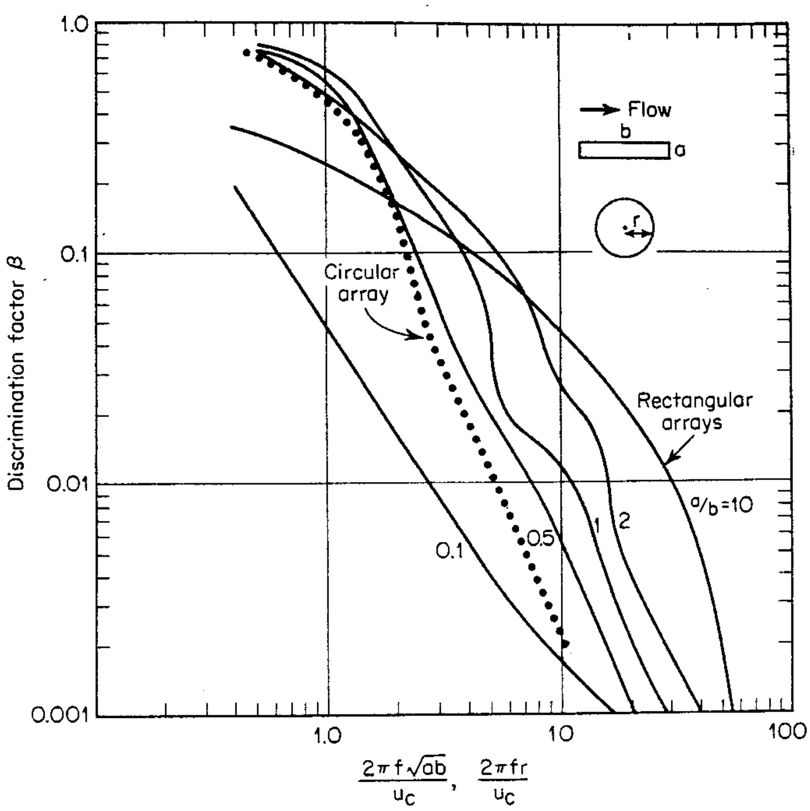


fig. 11.8 *Discrimination of rectangular and circular arrays against flow noise. The sides a and b of the rectangular array are oriented perpendicular and parallel to the direction of flow, respectively.* [*After White (9) and Corcos (8).*]

As an example, at a speed of 2.0 knots, $M = 7 \times 10^{-4}$, and the quantity 10 log (β/β_{iso}) becomes −70 dB. In actual practice on a moving vessel, however, such great benefits of large arrays for reducing noise are not likely to be observed because of the existence of sources of noise other than the turbulent-flow pressures on the rigid wall. If the wall is not rigid, resonant wall vibration as well as the radiated noise of distant turbulence are likely to overwhelm the ideal flow-noise pressures picked up by a large array.

11.4 Flow-Noise Reduction

For a well-streamlined body with a minimum of vanes, fins, and appendages, various techniques can be used to reduce the sensitivity to flow noise of a hydrophone located on it. Some of these are:

1. *Make the hydrophone larger.* The effect of a larger hydrophone size is to cause the turbulent flow-noise pressures to average out as a result of their small correlation distance. In wind and water tunnels, reductions of 40 dB or more can be obtained in this way, but on moving bodies such great reductions

cannot be achieved, as mentioned above, because of effects such as shell vibration and the flow-excited radiated noise of fins and other appendages.

2. *Move the hydrophone forward.* A forward location is quieter than one toward the tail of the body because of a thinner boundary layer and a greater distance from the noise-producing surfaces at the rear of the body. The quietest place of all is right at the nose itself in the region of the "stagnation point" where the flow separates; here the boundary layer is absent, and flow noise is received only by radiation and diffraction around the front of the body. Figure 11.9 shows diagrammatically the output of a hydrophone at a forward location and one toward the stern of a streamlined body in the turbulent boundary layer. A hydrophone located at the nose of a blunt-nose body picks up the radiated noise of the turbulence by diffraction around the nose, as shown by the experimental work of Lauchle in a water tunnel (10).

3. *Remove the hydrophone from the turbulent boundary layer.* This can be done by placing it in a cavity or in a recess in the wall. The effect here is to allow the positive and negative pressures to cancel out, in much the same way as with a hydrophone of larger size.

4. *Eject polymer fluids.* The ejection of very small amounts of polymers consisting of long-chain unbranched molecules of high molecular weight (about 10^6) has been found effective in the reducing fluid drag in pipes and on moving bodies. The drag-reduction process appears to be one of thickening the laminar sublayer (Fig. 11.6) and thereby reducing self-noise by separating the hydrophone from the turbulent boundary layer, as in technique 3 above. The concentration of polymer found to be effective is very low (100 parts per million or less), and, on a moving body, ejection can be achieved through holes in the nose. Long-chain polymers are viscoelastic fluids that cause the solution to be non-Newtonian: that is, they cause the shear stress to be no longer linearly proportional to the rate of shear. Just how their effect on

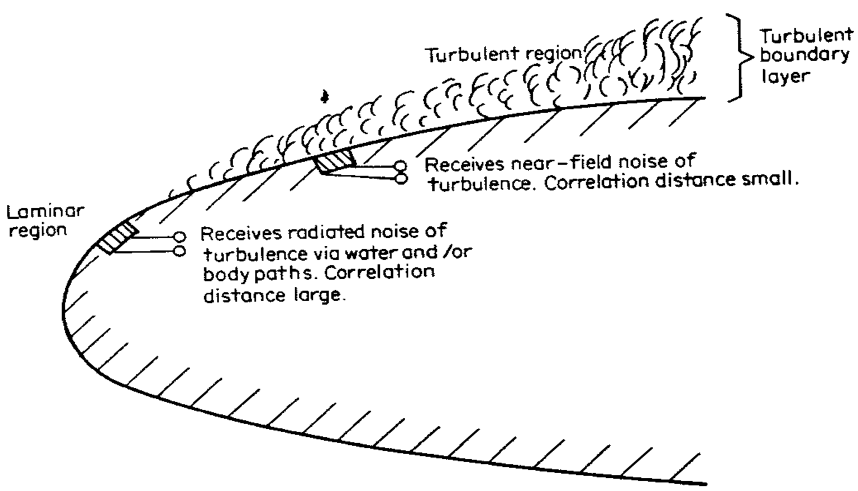


fig. 11.9 Response of a hydrophone on a streamlined body in the laminar and turbulent regions of the flow.

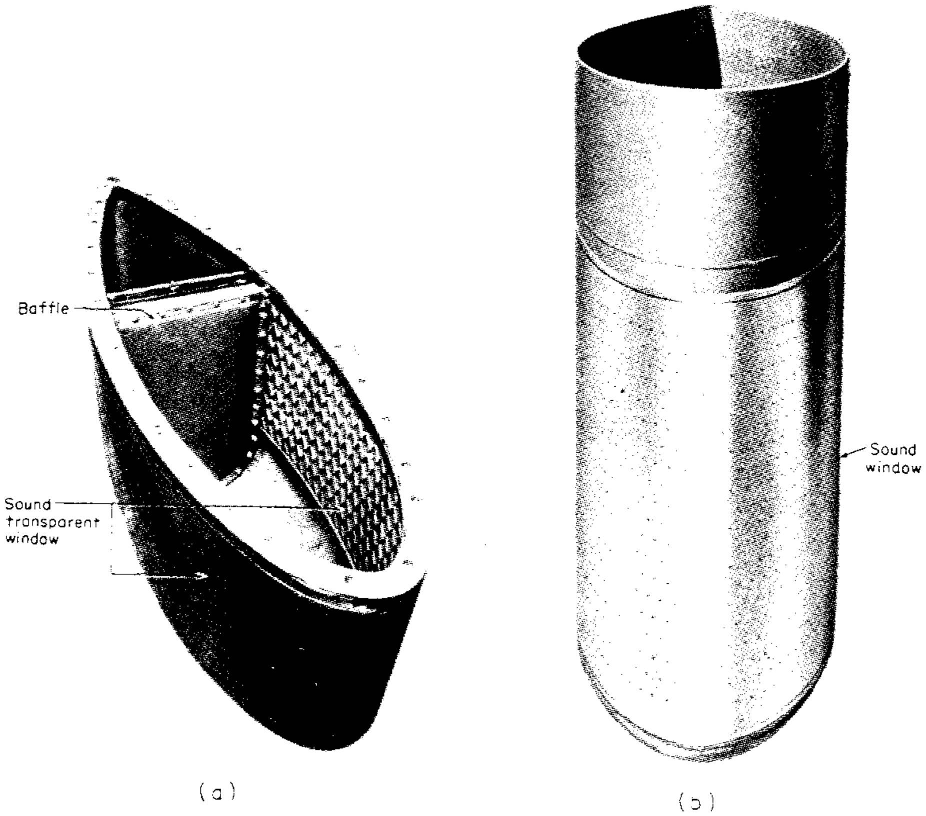
the boundary layer occurs is uncertain; one idea is that the long-chain molecules tend to align themselves parallel to the wall and thereby inhibit the formation of stress differences normal to the wall that result in the formation of turbulence. On a self-propelled body like a torpedo, polymer ejection has an added beneficial effect on self-noise in that, by reducing drag, the propulsive power needed to achieve a given speed is less; in other words, the machinery and propeller contributions to self-noise are lower. The hydrodynamic effects of polymer ejection have received much attention in the literature, and an excellent review paper by Hoyt (11) containing many references has been published.

11.5 Domes

It was observed many years ago that large reductions of what is now known as hydrodynamic noise could be achieved on surface ships by surrounding the sonar transducer by a streamlined housing. Such housings are called *sonar domes*. They reduce self-noise by minimizing turbulent flow, by delaying the onset of cavitation, and by transferring the source of flow noise to a distance from the transducer. Sonar domes were originally spherical in shape but were soon streamlined into a teardrop shape to prevent the occurrence of cavitation at high speeds. Some examples of domes used during World War II are shown in Fig. 11.10. The domes in this figure are of all-metal construction and have a thin stainless steel window to permit the ready exit and entrance of sound out of and into the transducer inside. Modern domes are constructed of rubber reinforced with thin steel ribs. Many have baffles, such as those seen in Fig. 11.10*a* and 11.10*c*, to reduce machinery and propeller noises coming from the rear.

The acoustic and mechanical requirements of dome design are severe. The dome must be acoustically transparent, so as to introduce only a small transmission loss and produce no large side lobes in the directivity pattern of the enclosed transducer. The latter requirement means the absence of internal specular reflection from the dome walls. At the same time the dome should be sufficiently streamlined to delay the onset of cavitation on its surface beyond the highest speed reached by the vessel and should be of sufficient mechanical strength to resist the hydrodynamic stresses upon it when under way. These requirements are to a large extent mutually incompatible.

Expressions have been obtained theoretically (12, 13) and generally verified experimentally for the transmission loss and the specular reflection produced by a dome of a given material and wall thickness on a transducer of given frequency, directivity, and position in the dome. Both the transmission loss and reflectivity of the dome increase with frequency and with the thickness and density of the dome walls. Internal reflections in domes can be greatly reduced by increasing the horizontal, and particularly the vertical, curvature of the dome walls. Hence, for both acoustic and hydrodynamic reasons, sonar domes employ materials as thin and light as possible formed into curved



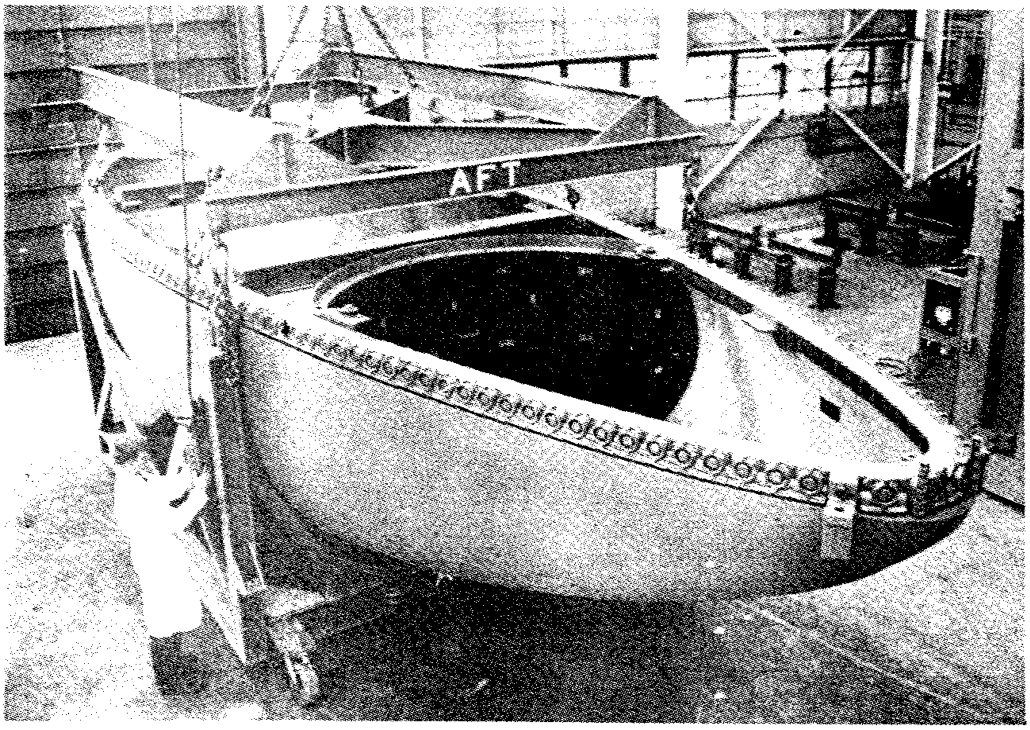


fig. 11.10 *Photographs of streamlined domes. (a) QBF dome. (b) QGA dome. (c) A modern surface ship dome; note the curved baffle in this dome. (a, b, from Ref. 14; c, courtesy B. F. Goodrich Co., Akron, Ohio.)*

streamlined shapes. The acoustic windows of sonar domes used during World War II, like those of Fig. 11.10, ranged from 0.020 to 0.060 in. in thickness (14).

For low self-noise, sonar domes must be kept undamaged and free of marine fouling. A dome with a rough exterior surface will produce a higher flow noise, as well as noise caused by local cavitation at "hot spots" on its surface at the higher speeds of the vessel on which it is mounted.

For many years the sonar domes of surface ships were located aft of the bow, and were retractable for use in shallow water and for ease of dry docking. However, the recent trend toward lower frequencies, higher powers, and larger sizes of modern sonars has required a shift in location and an abandonment of the rectractable feature of sonar domes. The dome of the A/N-SQS 26 sonar is located just at the bow and is bulbous in shape to accommodate the tremendous size of the transducer (Fig. 11.11). It is about 50 ft long, 10 ft high, and 18 ft wide, and weighs some 40 tons. Compared to older installations, the location and size of this dome has both benefits and disadvantages. It is as far removed from the propellers as is possible with a hull installation,

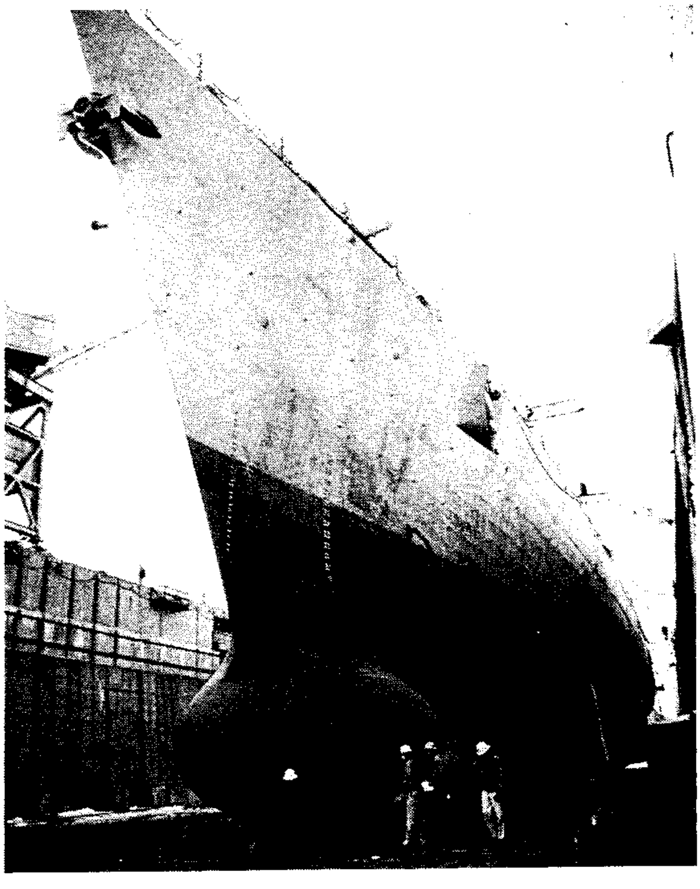


fig. 11.11 *The A/N-SQS 26 pressurized sonar dome with rubber window on the USS "Willis A. Lee" (DL-4) in drydock. (Photo courtesy of B. F. Goodrich Company.)*

and so experiences a lower level of propeller noise. The bulbous shape of the bow reduces—rather than increases—the drag of hull in its motion through the water, and is said to reduce pitching of the ship as well. On the other hand, the draft of the vessel is increased, and the drydocking operation is made more complicated. The alternative to such a large dome is to use the sides and length of the vessel to provide the necessary surface area for efficient power radiation and directivity, but the problems of element phasing and interaction in this kind of array are formidable.

11.6 Self-Noise of Cable-Suspended and Bottomed Hydrophones

Hydrophones that are hung from the end of a cable are likely to suffer from a peculiar kind of noise called *strumming* or *flutter* noise. This form of self-noise occurs in a current of water, and is the result of cable vibration induced by the eddies or vortices shed by the cable. This is the "aeolian harp" effect, or the singing of telephone wires in a wind, that has long been known in air acoustics (15). The frequency of vortex shedding is given by the simple expression $f = Sv/d$, where S is the dimensionless "Strouhal number," v is the water current speed, and d is the cable diameter in the units of length of v. The Strouhal number happens to be a constant equal to 0.18 over much of the range of current speeds and cable sizes occurring in practice. Thus, with a 1-cm-diameter cable in a 1-knot current (51.5 cm/s), the strumming frequency will be 9 Hz. Strumming noise can be readily alleviated by a number of means, including using a faired cable, keeping the natural frequency of cable vibration well separated from the strumming frequency, isolating the hydrophone from the cable (as by such simple means as suspending it from the cable by rubber bands), and employing a hydrophone having an acceleration canceling design.

Another malady of cables is *triboelectric noise* or the spurious voltages resulting from friction ("tribo") between the cable conductor and the shield. Any motion of the cable tends to produce varying frictional charges in the cable dielectric; these appear as voltages at the end of the cable. They occur in voids or gaps between the conductor and the dielectric that act as variable air capacitors. Triboelectric noise exists whenever the cable is bent or altered in shape; it enhances the effect of cable strumming. It can be alleviated by coating the dielectric with graphite (Aquadag) or by binding the dielectric material tightly to the conductors. This kind of noise has been investigated empirically with various kinds of cables subjected to different kinds of deformation (16), and a number of low-noise cables are commercially available.

Hydrophones resting on the ocean floor are susceptible to the motional effects of water currents flowing past, and around, the hydrophone and its mounting. Strasberg (17) has discussed and made quantitative estimates of the apparent noise caused by the impingement of the turbulent and thermal microstructure carried along by a current and striking a hydrophone. Vortices and turbulences shed by the hydrophone and its structure are also a form of low frequency nonacoustic noise, as shown by laboratory measurements of McGrath et al. (18). These current-produced pseudonoises make difficult valid measurements of the infrasonic ambient background of the sea, especially in shallow water, and require careful design of the hydrophone structure, as well as a thermal shield around the hydrophone for quiet operation at frequencies below 20 Hz.

11.7 Self-Noise of Towed Sonars

A sonar housed in a streamlined body and towed at a depth behind a surface craft (see Fig. 1.2) is subject to a wide variety of self-noise sources. These range from "pure" flow noise—the pressure fluctuations of the boundary layer adjacent to the hydrophone—to vibrations of the towing cable.

Some direct field trials of the noise of hydrophones inside a towed streamlined body of revolution have been made by Nishi, Stockhausen, and Evensen (19). The body they used was 6 ft long and 1½ ft in maximum diameter. A number of small hydrophones 0.07 in. in diameter were placed on it for self-noise measurements at various places along its length. Towing was done by a hydrofoil craft at speeds up to 30 knots. It was found during the field trials that a hydrophone along the side of the body, where the turbulent boundary layer was well developed, picked up mainly flow noise at frequencies above 1 kHz; its levels were not greatly different from those of the buoyant body shown in Fig. 11.7, when allowance is made for hydrophone size. A hydrophone at the nose was found to be quieter than the one located along the side of the body. This sensor picked up the radiated noise of the towing craft, together with the wall vibrations caused by vibrations of the tow cable and the tail-fin structure of the body.

Another kind of towed sonar is a *flexible-line hydrophone array* towed at a considerable distance (up to several miles) behind a surface craft to reduce pickup of the noise from the towing vessel. This is the successor of the "eel" worked on the World War I (Sec. 1.1); more recently towed lines have been extensively used in waterborne seismic prospecting for oil (20). Typically, a seismic "streamer" consists of 24 or more hydrophone groups, each up to several hundred feet long, and having an overall length of about 8,000 feet (21, 22). The hydrophones are placed inside a thin-walled flexible plastic jacket, typically 2½ in. in diameter, filled with a fluid of low specific gravity so as to be nearly neutrally buoyant. In the shallow water of waterborne prospecting, a constant depth is maintained by dynamic controllers or "birds," which themselves are a source of noise for hydrophones near them. Fig. 11.12 shows smoothed measured spectra of a hydrophone group in a streamer towed at two speeds a distance of 1,000 feet behind the towing vessel in sea states 0 to 1. Added for comparison is an average curve of the ambient noise level for a wind speed of 6 knots at seven Pacific Ocean locations, due to Wenz (Fig. 7.8).

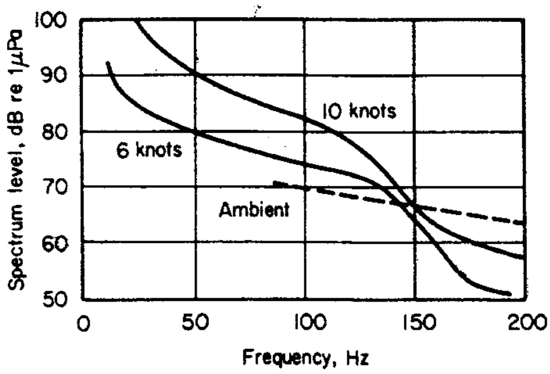


fig. 11.12 Seismic streamer self-noise spectrum levels at two towing speeds, and the ambient-noise spectrum for a wind speed of 6 knots in shallow water as given by Wenz (Fig. 7.8). (After Ref. 22.)

Although towed arrays do reduce greatly the radiated noise of the ship by means of their distance and directivity, they are subject to various motional effects and to various forms of hydrodynamic noise, including "pure" flow noise. Especially deleterious are the results of vibration induced by towing, which causes effects such as acceleration response in the array hydrophones, hydrostatic pressure changes due to the vertical motion of the array, changing pressures in the oil filling of the flexible hose, and vortex shedding by the vibrating tow cable. Nevertheless, flexible towed-line arrays make possible the rapid exploration for oil in coastal areas and, as passive sonars, provide a capability for listening from surface ships to low frequencies and in stern directions—something that hull-mounted sonars do not possess.

11.8 Self-Noise Levels

Figure 11.13 shows equivalent isotropic self-noise levels at 25 kHz on a number of World War II American and British destroyers. These data, taken from

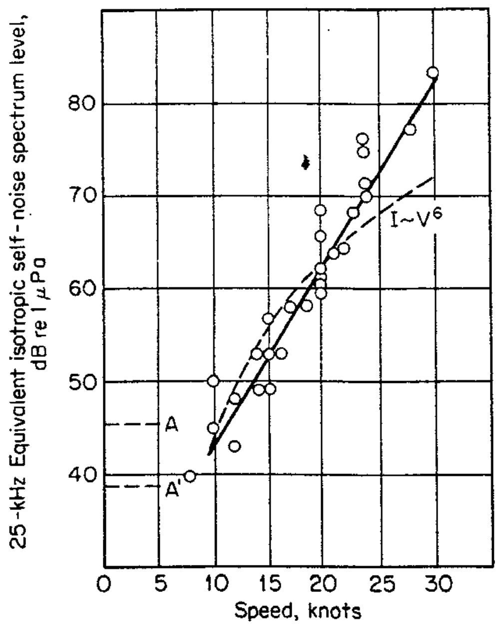


fig. 11.13 Equivalent isotropic spectrum levels at 25 kHz on destroyers (Ref. 23). The levels A and A′ are deep-sea ambient levels at sea states 3 and 6. The dashed curve shows the theoretical variation with speed of flow noise.

a wartime study of Primakoff and Klein (23), were obtained with various sonar transducers of differing directivity, and have been corrected to equivalent isotropic levels, as discussed above, by allowing for (adding) the directivity index of the transducer. The curved line shows an increase of self-noise intensity as the sixth power of the speed, in agreement with theoretical expectations for the speed variation of flow noise. Although higher noise levels are observed at high speeds, probably because of dome cavitation and other sources of noise, the general agreement suggests the dominance of some form of flow noise in these data at moderate speeds.

Figure 11.14 is a similar plot for small warships of the PC and SC classes and for British DE-type ships and frigates. Here the increase of noise with speed is much more rapid and suggests the dominance of propeller cavitation noise in these smaller ships, on which the sonar dome, its distance from the propellers, and the amount of screening by the hull are all much smaller than on destroyers.

The levels of Figs. 11.13 and 11.14 apply for forward bearings, when the directional transducer in its dome is trained in a forward direction. When it is trained toward the stern of the ship, higher levels are observed, particularly on small ships, due to the noise of the cavitating propeller.

At the lower frequencies more typical of modern destroyers, the same sort of behavior with speed as that shown in Fig. 11.13 is observed. Figure 11.15 is representative of modern destroyer sonars operating at frequencies of 10 kHz and below. At very slow speeds, or when lying to, the sonar self-noise level is close to the ambient background level of the sea in the prevailing sea state. At speeds between 15 and 25 knots the self-noise level increases sharply with speed at the rate of about 1½ dB/knot, and represents the domi-

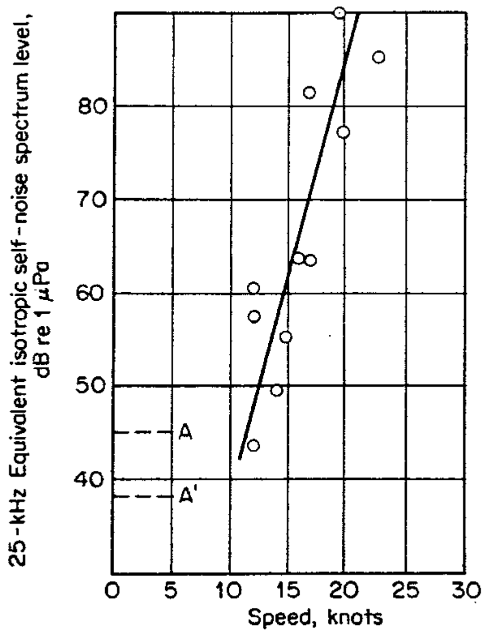


fig. 11.14 *Equivalent isotropic spectrum levels at 25 kHz on American PC and SC class ships and on British DE types and frigates. A and A′ are ambient levels at sea states 3 and 6. (Ref. 23.)*

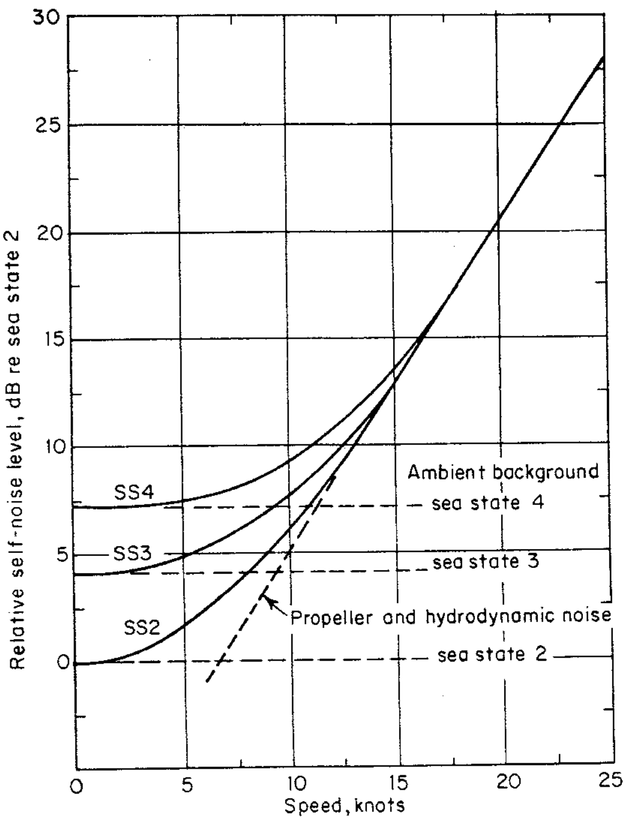


fig. 11.15 Self-noise levels versus speed on a modern destroyer.

nant contributions of hydrodynamic and propeller noise to the total noise level.

Self-noise levels on submarines are illustrated in Fig. 11.16*a* and *b*. These show average spectra ad the increase of noise with speed measured during World War II with the JP-1 listening equipment. The JP sonar had a 3-ft horizontal line hydrophone mounted on the deck of the submarine forward of the conning tower and could be trained manually so as to listen in different directions. The spectra of Fig. 11.16*a* are for noisy, average, and quiet installations at a speed of 2 knots. They approximate the levels of deep-water ambient noise at the high-frequency end, but rise more rapidly with decreasing frequency, probably as a result of machinery-noise contributions. The extremely rapid rise with speed suggests the influence of propeller cavitation as the speed increases, as does the fact that the self-noise of the JP-1 sonar decreased with increasing depth of submergence (24). In other submarine sonars, less exposed to cavitation noise, the effect of speed is less marked and approximates the rate of rise of 1½ to 2 dB/knot found on destroyer-like surface ships (Fig. 11.13).

Just as for destroyers, the self-noise of submarines observed with the JP-1 sonar was found to be independent of bearing on forward bearings but to increase sharply as the hydrophone was trained toward the stern. Examples of the "directivity pattern" of self-noise at several speeds are given in Fig. 11.17.

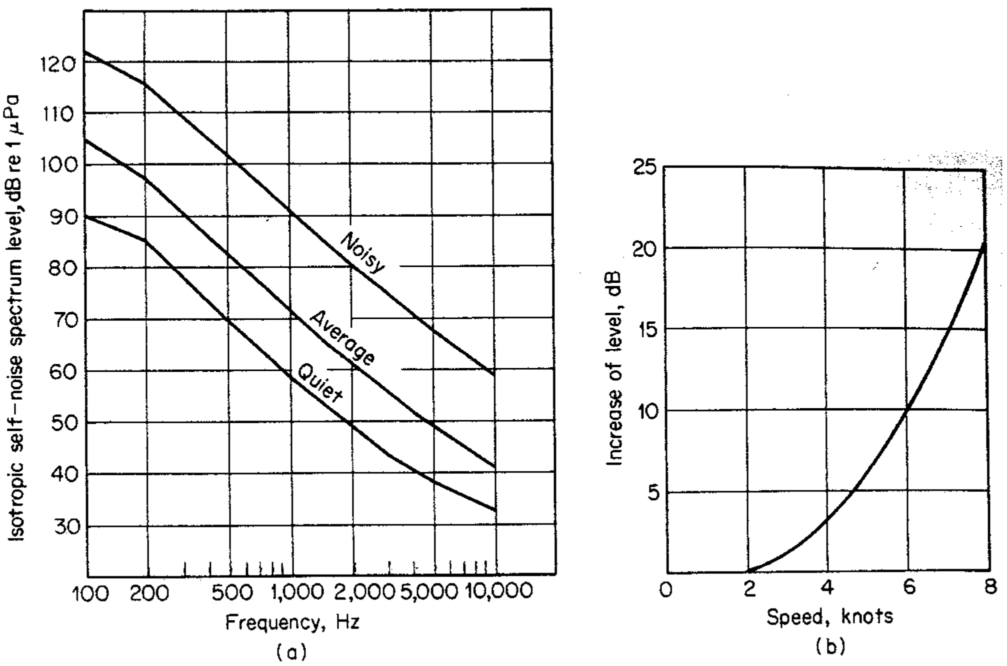


fig. **11.16** *Average self-noise spectra on submaries: (a) JP-1 data, forward bearings, speed 2 knots, periscope depth. (b) Increase of noise level with speed relative to 2 knots. (Ref. 25, figs. 9 and 10.)*

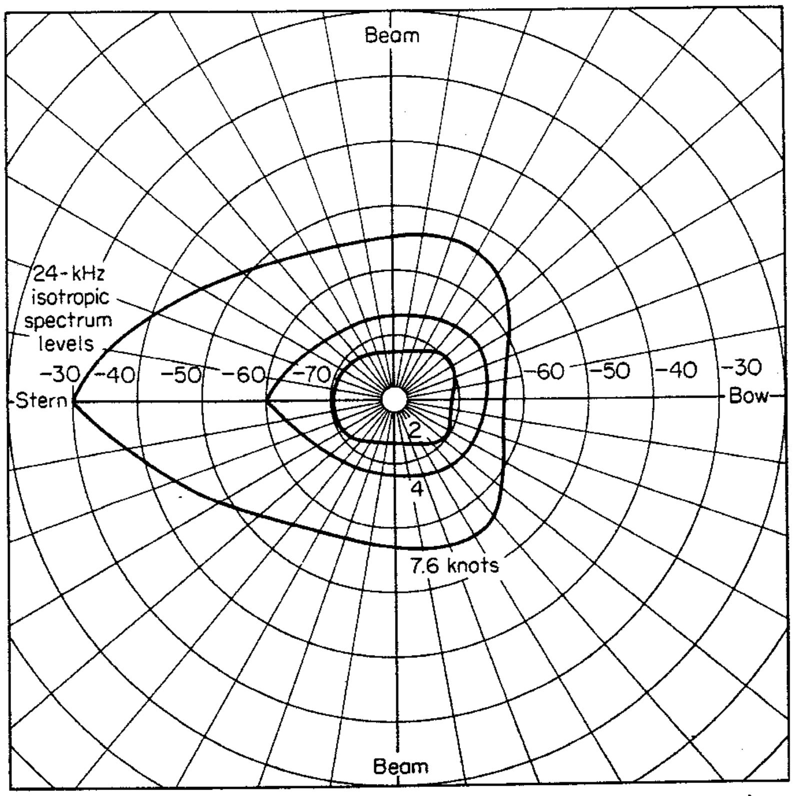


fig. **11.17** *Directionality of high-frequency self-noise at various speeds. Hydrophone directivity index assumed to be 20 dB. (Ref. 24.)*