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R adiated noise of ships, submarines, nd torpedoes: 'adiated-noise levels

Ships, submarines, and torpedoes are excellent sources of underwater sound. Being themselves machines of great complexity, they require numerous rotational and reciprocating machinery components for their propulsion, control, and habitability. This machinery generates vibration that appears as underwater sound at a distant hydrophone after transmission through the hull and through the sea. Of particular importance is the machinery component called the propeller, which serves to keep the vehicle in motion, and in doing so, generates sound through processes of its own.

Radiated noise is of particular importance for passive sonars, which are designed to exploit the peculiarities of this form of noise and to distinguish it from the background of self-noise or ambient noise in which it is normally observed.

In this chapter the principal characteristics of radiated noise will be discussed, and some data on the level of this noise for various vehicles will be presented. The discussion will be restricted to conventional designs and conventional propulsion systems, omitting any discussion of the noise of nuclear-propelled vessels or unusual propulsion methods. The word "vessel" will be used to refer to surface ships, submarines, or torpedoes indiscriminately when it is unnecessary to distinguish among them.

10.1 Source Level and Noise Spectra

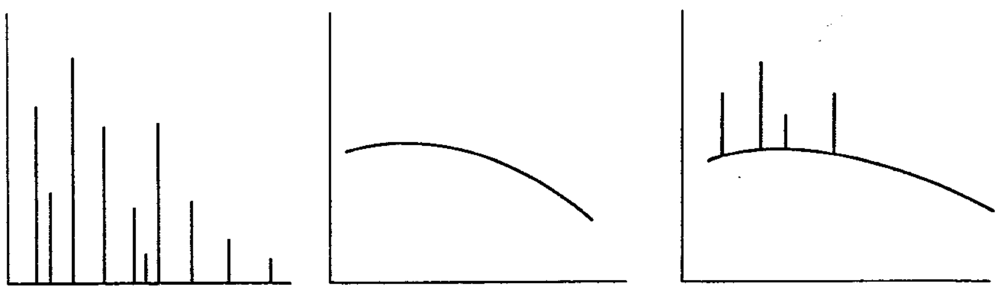
The parameter *source level* for radiated noise in the sonar equations is the intensity, in decibel units, of the noise radiated to a distance by an underwater source, when measured at an arbitrary distance and reduced to 1 yd from the *acoustic center* of the source. By acoustic center is meant the point inside or outside the vessel from which the sound, as measured at a distance, *appears* to be radiated. Practically speaking, radiated-noise measurements must of necessity be made at a distance from the radiating vessel, typically 50 to 200 yd, and must be reduced to 1 yd by applying an appropriate spreading or distance correction. Source levels are specified in a 1-Hz band, and will be referred to a reference level of 1 μPa. The source levels for radiated noise are accordingly *spectrum* levels relative to the 1-μPa reference level.

When 1 meter is used as the reference distance instead of 1 yd, a correction of -0.78 dB must be applied to source levels referred to 1 yd. This same correction is required for all the other range-dependent sonar parameters when using 1 meter instead of 1 yd as the unit of range.

Noise spectra are of two basically different types. One type is *broadband noise* having a continuous spectrum. By continuous is meant that the level is a continuous function of frequency. The other basic type of noise is *tonal noise* having a discontinuous spectrum. This form of noise consists of tones or sinusoidal components having a spectrum containing *line components* occurring at discrete frequencies. These two spectral types are illustrated diagrammatically in Fig. 10.1. The radiated noise of vessels consists of a mixture of these two types of noise over much of the frequency range and may be characterized as having a continuous spectrum containing superposed line components.

10.2 Methods of Measurement

The noise radiated by vessels is nearly always measured by running the vessel past a stationary distant measurement hydrophone. Various types of hydrophones and hydrophone arrays have been employed for this purpose. The simplest arrangement uses a single hydrophone hung from a small measurement vessel. More elaborate configurations involve an array of hydrophones, either strung in a line along the bottom in shallow water, or hung vertically in



(a) (b) (c)

fig. 10.1 Diagrams of (a) line-component spectrum, (b) continuous spectrum, and (c) composite spectrum obtained by superposing (a) and (b).

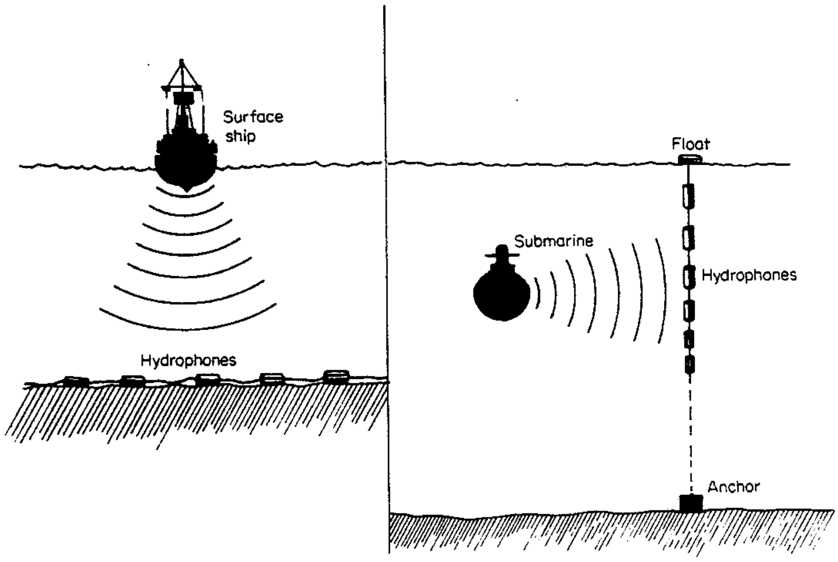


fig. 10.2 Arrangements of hydrophones used at sound ranges for measuring radiated noise.

deep water, as illustrated in Fig. 10.2. The former arrangement is suitable for measuring the noise of surface ships, and the latter is useful for measuring the noise of submarines or torpedoes running at deep depths. In both cases the vessel under test is arranged to run at a constant speed and course so as to pass the measurement hydrophones at a known distance. Suitable techniques are used to determine the range of the vessel while its radiated-noise output is being measured. During the run, broadband tape recordings are made, and later subjected to analysis in different frequency bands.

Figure 10.3 shows the instrumentation employed at the Atlantic Undersea Test and Evaluation Center (AUTEC) for the measurement of the radiated noise of submarines. An elaborate system is used for tracking the submarine during its passage past the measurement hydrophones. This noise-measurement range is located in the "Tongue of the Ocean" east of the Bahama Islands.*

Although radiated noise is commonly expressed as *spectrum levels*, that is, in 1-Hz bands, frequency analyses are often made in wider bands. The results are reduced to a band of 1 Hz by applying a bandwidth reduction factor equal to 10 times the logarithm of the bandwidth used. That is to say, if BL is the noise level measured in a band w hertz wide, the spectrum level in a 1-Hz band is BL $-$ 10 log w (Sec. 1.5). This reduction process is valid for continuous "white" noise having a flat spectrum; it can be shown to be also valid for noise having a continuous spectrum falling off at the rate of -6 dB/octave, if the center frequency of the band is taken to be the geometric mean of the two

* Five papers on AUTEC were presented at the 74th meeting of the Acoustical Society of America in 1967. Abstracts appear in *J. Acoust. Soc. Am.*, **42**:1187 (1967).

ends of the frequency band. But for line-component noise containing one or several strong lines within the measurement bandwidth, this reduction process is not valid and yields spectrum levels lower than the level of the line component dominating the spectrum. In short, the nature of the spectrum must in principle be known before the reduction is made. Many old reported data are almost useless at low frequencies because an excessively broad frequency band had been employed in the original analysis.

Similarly, a correction for distance is required to reduce the measurements to the 1-yd reference distance. The ubiquitous spherical-spreading law is generally applied for this purpose. Several investigations have indicated that spherical or inverse-square spreading is a good rule of thumb for expressing the variation of ship noise with range at close distances, even for low frequencies in shallow water (1). In any case, in spite of the apparent artificiality of the reduction processes in many instances, the original levels can be recovered from the published reduced values if the reduction process, bandwidth, and measurement distance are stated.

Studies of the sources of noise under various operating conditions, as distinct from measurements of noise level alone, have employed various clever schemes to pinpoint the dominant sources of noise. For example, when ships and torpedoes are run very close to the measuring hydrophone, the principal source of noise—whether machinery noise originating amidships or propeller noise originating near the stern—can be identified by the correspondence between the peak of the noise and the closest part of the ship at that instant. Overside surveys (2) of surface ships and submarines, in which a hydrophone

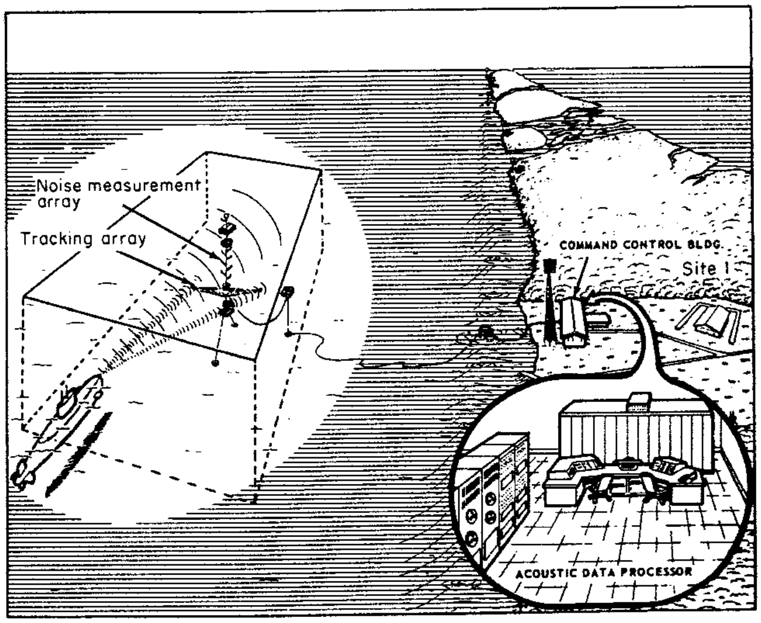


fig. 10.3 *Noise measurement range at the Atlantic Undersea Test and Evaluation Center (AUTEC).*

is lowered over the side of the moored vessel, are sometimes made to measure the noise radiated into the water by different pieces of ship's machinery. Various modifications to a running vessel have been made to study their effect on the noise output; such modifications include towing a surface ship without its propeller and operating a torpedo in a "captive" condition alongside a measurement platform. The effect of a bubble screen has been simulated by turning a ship so as to cross its own wake and noting the effect on the self-noise and radiated noise. All these methods have contributed to our present knowledge of the sources of radiated noise.

10.3 Sources of Radiated Noise

The sources of noise on ships, submarines, and torpedoes can be grouped into the three major classes listed in Table 10.1. *Machinery noise* comprises that part of the total noise of the vessel caused by the ship's machinery. *Propeller noise* is a hybrid form of noise having features and an origin common to both machinery and hydrodynamic noise. It is convenient to consider propeller noise separately because of its importance. *Hydrodynamic noise* is radiated noise originating in the irregular flow of water past the vessel moving through it and causing noise by a variety of hydrodynamic processes.

table 10.1 Source of Radiated Noise (Diesel-Electric Propulsion)

Machinery noise:
Propulsion machinery (diesel engines, main motors, reduction gears)
Auxiliary machinery (generators, pumps, air-conditioning equipment)
Propeller noise:
Cavitation at or near the propeller
Propeller-induced resonant hull excitation
Hydrodynamic noise:
Radiated flow noise
Resonant excitation of cavities, plates, and appendages
Cavitation at struts and appendages

Machinery noise Machinery noise originates as mechanical vibration of the many and diverse parts of a moving vessel. This vibration is coupled to the sea via the hull of the vessel. Various paths, such as the mounting of the machine, connect the vibrating member to the hull. Machine vibration can originate in the following ways:

1. Rotating unbalanced parts, such as out-of-round shafts or motor armatures
2. Repetitive discontinuities, such as gear teeth, armature slots, turbine blades
3. Reciprocating parts, such as the explosions in cylinders of reciprocating engines

4. Cavitation and turbulence in the fluid flow in pumps, pipes, valves, and condenser discharges
5. Mechanical friction, as in bearings and journals

The first three of these sources produce a *line-component spectrum* in which the noise is dominated by tonal components at the fundamental frequency and harmonics of the vibration-producing process; the other two give rise to noise having a *continuous spectrum* containing superposed line components when structural members are excited into resonant vibration. The machinery noise of a vessel may therefore be visualized as possessing a low-level continuous spectrum containing strong line components that originate in one or more of the repetitive vibration-producing processes listed above.

A diagrammatic view of the sources of machinery noise aboard a diesel-electric vessel is shown in Fig 10.4. Each piece of machinery produces periodic vibrational forces at the indicated fundamental frequency and thereby generates a series of line components at this frequency and at its harmonics. However, at a distance in the sea, the sound produced by these vibrational forces depends not only on their magnitude, but also on how such forces are transmitted to the hull and coupled to the water. A notable example is the resonant excitation of large sections of the hull by machinery vibration—called "hull drone"—such as that produced by the rotation of the massive propeller shaft, wherein certain frequencies of the excitation spectrum are reinforced by a short of sounding-board effect. The manner of mounting of the machine and the resulting vibration of the hull are determining factors in the radiation of sound. Another source of variability is in the propagation of different fre-

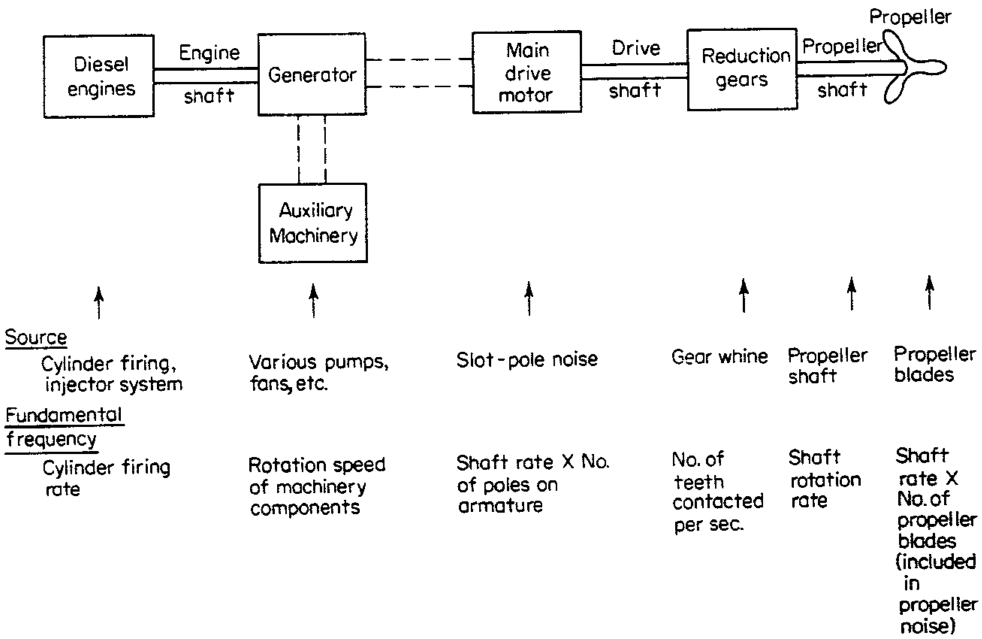


fig. 10.4 *Machinery components and noise sources on a diesel-electric vessel.*

quencies to a distant point in the sea. Because of these various effects, the harmonic structure of radiated noise is complex, and the line-component series generated by even a single source of noise is irregular and variable. When many noise sources are present, as in a vessel under way, the machinery-noise spectrum contains line components of greatly different level and origin, and is, consequently, subject to variations of level and frequency with changing conditions of the vessel.

Propeller noise Even though the propeller is a part of the propulsion machinery of a vessel, the noise it generates has both a different origin and a different frequency spectrum from machinery noise. As just described, machinery noise originates *inside* the vessel and reaches the water by various processes of transmission and conduction through the hull. Propeller noise, on the other hand, originates *outside* the hull as a consequence of the propeller action and by virtue of the vessel's movement through the water. The location of the sources of noise along the hull is different as well. When a vessel passes close to a nearby hydrophone, it is observed that noises ascribable to the vessel's machinery reach a peak level *before* those originating at the propellers, in keeping with the place of origin aboard the noise-producing vessel.

The source of propeller noise is principally the noise of cavitation induced by the rotating propellers. When a propeller rotates in water, regions of low or negative pressure are created at the tips and on the surfaces of the propeller blades. If these negative (tensile) pressures become high enough, physical rupture of the water takes place and cavities in the form of minute bubbles begin to appear. These cavitation-produced bubbles collapse a short time later—either in the turbulent stream or up against the propeller itself—and in so doing emit a sharp pulse of sound. The noise produced by a great many of such collapsing bubbles is a loud "hiss" that usually dominates the high-frequency end of the spectrum of ship noise when it occurs. The production and collapse of cavities formed by the action of the propeller is called propeller cavitation.

Propeller cavitation may be subdivided into *tip-vortex cavitation*, in which the cavities are formed at the tips of the propeller blades and are intimately associated with the vortex stream left behind the rotating propeller, and *blade-surface cavitation*, where the generating area lies at front or back sides of the propeller blades. Of these two types of cavitation, the former has been found by laboratory measurements with model propellers and by analyses of field data (3) to be the more important noise source with propellers of conventional design.

Because cavitation noise consists of a large number of random small bursts caused by bubble collapse, it has a continuous spectrum. At high frequencies, its spectrum level *decreases* with frequency at the rate of about 6 dB/octave, or about 20 dB/decade. At low frequencies, the spectrum level of cavitation noise *increases* with frequency, although this reverse slope tends to be obscured in measured data by other sources of noise. There is, therefore, a peak in the spectrum of cavitation noise which, for ships and submarines, usually occurs within the frequency decade 100 to 1,000 Hz. The location of the peak in the spectrum shifts to lower frequencies at higher speeds and (in the case of submarines) at smaller depths. Figure 10.5 shows diagrammatic cavitation-noise spectra for three combinations of speed and depth for a hypothetical submarine. The behavior of the spectral peak is associated with the generation of larger cavitation bubbles at the greater speeds and the lesser depths and with the resulting production of a greater amount of low-frequency sound. On an actual submarine, the variation of propeller noise with speed at a constant depth and with depth at a constant speed is illustrated by the measured curves of Fig. 10.6, which were obtained with a hydrophone placed 4 ft from the propellers on the two submarines, "Hake" and "Hoe."

It has long been known that as the speed of the ship increases, there is a speed at which propeller cavitation begins and the high-frequency radiated noise of the vessel suddenly and dramatically increases. This speed has been called the *critical speed* of the vessel. The submarines measures during World War II were observed to have critical speeds between 3 and 5 knots when operating at periscope depth and to have well-developed propeller cavitation at 6 knots and beyond. At speeds well beyond the critical speed, the noise of cavitation increases more slowly with speed. The noise-speed curve of a cavitating vessel accordingly has a shape like the letter S, with an increase of 20 to 50 dB at high frequencies when the speed is a few knots beyond the critical speed and with a slower rise, at a rate of 1.5 to 2.0 dB/knot, beyond. Measured data illustrating the S-shape characteristics of the noise-speed curve for submarines are shown in Fig. 10.7. The flattening of the curve at high speeds may be surmised to be due to a self-quenching or an internal absorption effect of the cloud of cavitation bubbles. Surface ships do not exhibit the S-shape feature in their noise-speed curves, but show, instead, a more gradual, and nondescript, increase of level with speed.

Cavitation noise is suppressed, and the critical speed is increased, by sub-

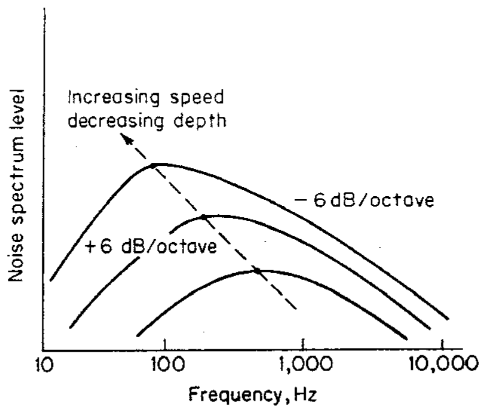


fig. 10.5 *Variation of the spectrum of cavitation noise with speed and depth.*

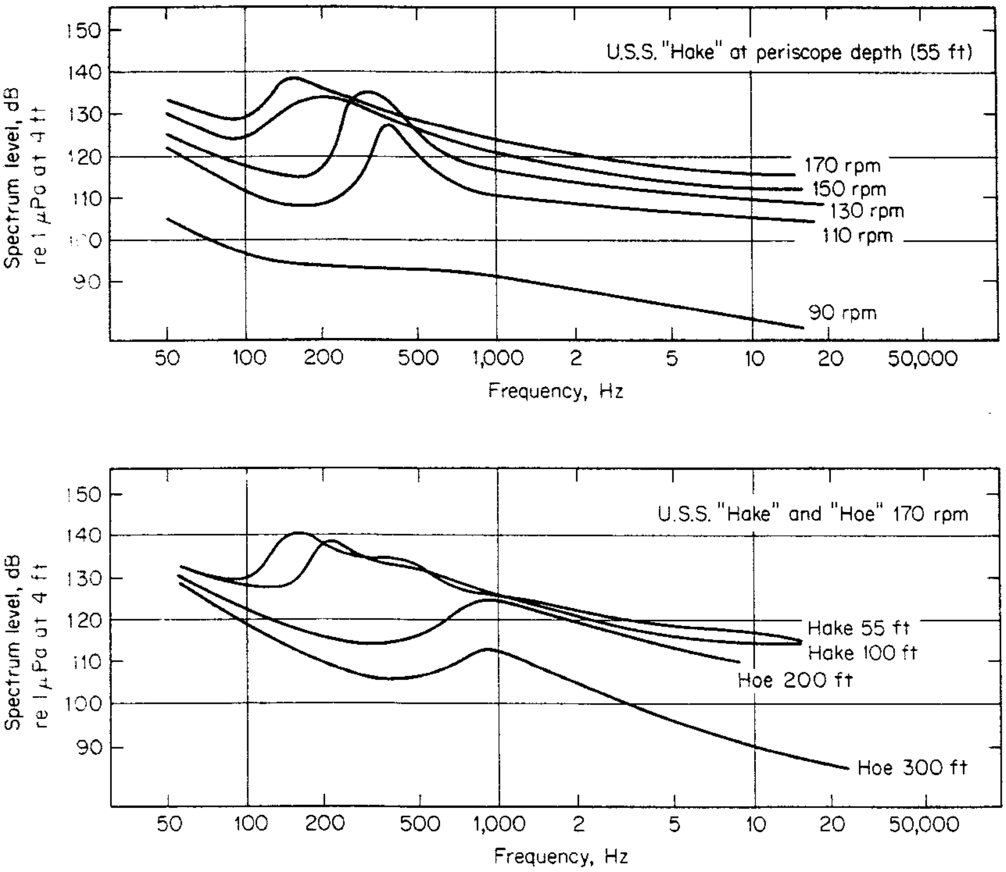


fig. 10.6 *Propeller noise as measured with a hydrophone located 4 ft from the tips of the propeller blades. World War II data on the submarines "Hake" and "Hoe." (Ref. 4.)*

merging to a greater depth. This effect has long been well known to submariners as a means to avoid detection. By simple hydrodynamic theory, it is known that the intensity of tip-vortex cavitation is governed by the *cavitation index*, defined by

$$K_T = \frac{p_0 - p_v}{(1/2)\rho v_T^2}$$

where p_0 = static pressure at propellers
p_v = vapor pressure of water
ρ = density of water
v_T = tip velocity of propeller blades

When K_T lies between 0.6 and 2.0, tip cavitation begins; when K_T is less than 0.2, the occurrence of cavitation is certain; when K_T is greater than 6.0, cavitation is unlikely. If it is assumed that cavitation begins at some fixed value of K_T and if p_v is neglected, we conclude that the critical speed must vary as the square root of the static pressure at the depth of the propellers. This is illustrated by the measurements on "Hake" and "Hoe" previously referred to.

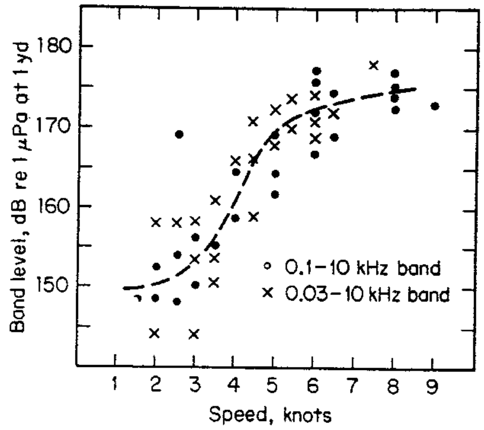


fig. 10.7 Broadband measurements of the radiated noise of a number of World War II submarines operating at periscope depth. 200-yd data reduced to 1 yd. (Ref. 4.)

For these submarines, Fig. 10.8 shows noise levels in the 10- to 30-kHz band observed with a hydrophone mounted 4 ft from the propeller tips and normalized by dividing by the square root of the hydrostatic pressure at the operating depth.

Although the cavitation noise of submarines is suppressed by depth, the reduction of noise with depth does not occur uniformly. When strong cavitation at high speeds occurs, the radiated noise of submarines is observed to first *increase* as the submarine dives, before the onset of the normal suppression of noise with depth. Figure 10.9 illustrates the effect of depth on the cavitation noise of a German type XXI submarine. At 8 knots, for example, this particular submarine had to submerge to 150 ft before experiencing the beginning of lower noise levels. This has been called the *anomalous depth effect,* although the term is now a misnomer, since it can be accounted for by theoretical analysis of cavitation-noise formation.

Many factors other than speed and depth affect propeller noise. A damaged propeller makes more noise than an undamaged one. More noise is made during turns and accelerations in speed than during uniform cruising. Truly anomalous conditions are sometimes found. "Singing" propellers generate strong tones between 100 and 1,000 Hz as a result of resonant excitation of the propeller by vortex shedding. The sound made by a singing propeller is

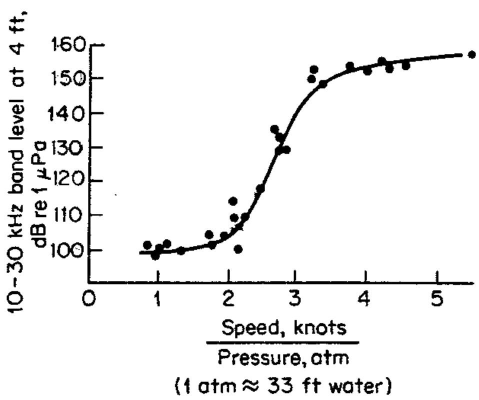


fig. 10.8 Normalized curves of cavitation noise. (Ref. 4.)

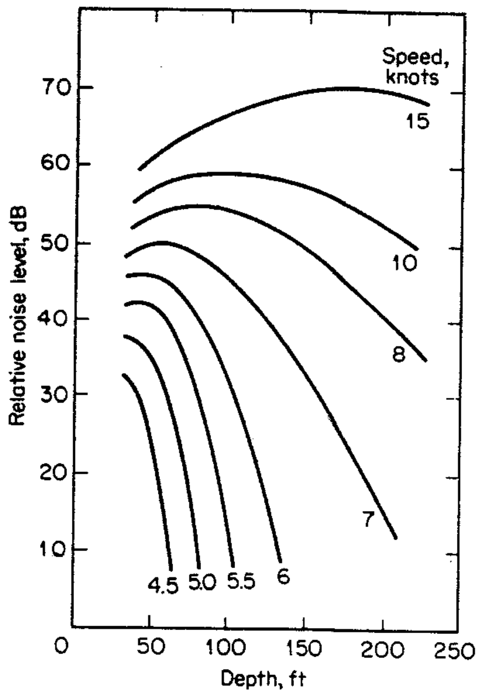


fig. 10.9 The anomalous depth effect, illustrated by measured wartime data at audio frequencies on a type XXI German submarine. Relative levels only.

very intense and can be heard underwater at distances of many miles. When it occurs, it can readily be cured, either by using a propeller made of a high-damping alloy or more simply, by changing the shape of the tips of the propeller blades (6).

Propeller noise is not radiated uniformly in all directions, but has a characteristic directional pattern in the horizontal plane around the radiating vessel. Less noise is radiated in the fore-and-aft directions than abeam, probably because of screening by the hull in the forward direction and by the wake at the rear. The dips in the pattern generally occur within 30° of the fore-and-aft direction, with the bow dip a few decibels deeper than the dip at the stern. A directivity pattern in the 2.5- to 5-kHz band for a freighter traveling at 8 knots is given in Fig. 10.10, where the contours show the locations, relative to the ship, of equal sound intensity on the bottom in 40 ft of water.

Propeller noise has been known for many years to be amplitude-modulated and to contain "propeller beats," or periodic increases of amplitude, occurring at the rotation speed of the propeller shaft, or at the propeller blade frequency equal to the shaft frequency multiplied by the number of blades. Propeller beats have long been used by listening observers for target identification and for estimating target speed. They have been observed (9) to be present in the noise of torpedoes as well as in the noise of ships and submarines. Propeller beats are most pronounced at speeds just beyond the onset of cavitation and diminish in the great roar of steady cavitation noise at high speeds.

Propeller noise, with its origin in the flow of water about the propeller, creates tonal components in addition to the continuous spectrum of cavitation noise. One tonal component is the "singing" tone of a vibrating singing propeller just mentioned. More normally, at the low-frequency end of the spectrum, propeller noise contains discrete spectral "blade-rate" components occurring at multiples of the rate at which any irregularity in the flow pattern into or about the propeller is intercepted by the propeller blades. The frequency of the blade-rate series of line components is given by the formula

$$f_m = mns$$

where f_m is the frequency, in hertz, of the mth harmonic of the blade-rate series of lines, n is the number of blades on the propeller, and s is the propeller rotation speed in number of turns per second. In one Russian experiment (10), these "blade" lines were observed with and without the emission of air bubbles around the propeller. At speeds when cavitation was well developed, they were found to be intimately associated with the cavitation process; in addition, line components not falling in the expected series were observed as well. Blade-rate line components were long ago observed (11) to be the dominant source of the noise of submarines in the 1- to 100-Hz region of the spectrum. It should be noted in passing that line components generated by the rotating propeller shaft—a form of machinery noise—fall in the same harmonic series as the blade-rate lines. Propeller noise, like machinery noise, can excite and be reinforced by the vibrational response of mechanical structures in the vicinity of the propeller.

The propellers of surface ships cavitate strongly at normal operating speeds. As a result, their low-frequency radiated noise spectrum is dominated by the blade-rate series of line components at the propeller blade frequency and its harmonics. Two examples of narrow-band spectra of surface ships—one a freighter, the other a supertanker—are shown in Fig. 10.11. The blade-rate series, with a fundamental frequency of about 8 Hz for both ships, is the principal feature of their radiation below about 50 Hz. The blade-rate series of

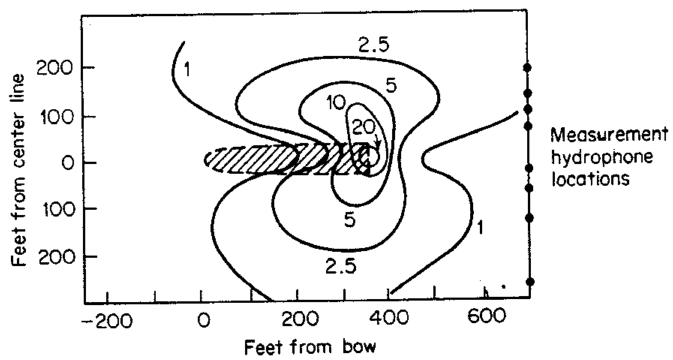


fig. 10.10 *Equal pressure contours on the bottom in 40 ft of water of a freighter at a speed of 8 knots. Contour values are pressures, in dynes per square centimeter in a 1-Hz band, at a point on the bottom, measured in the octave band, 2,500 to 5,000 Hz. (Ref. 8.)*

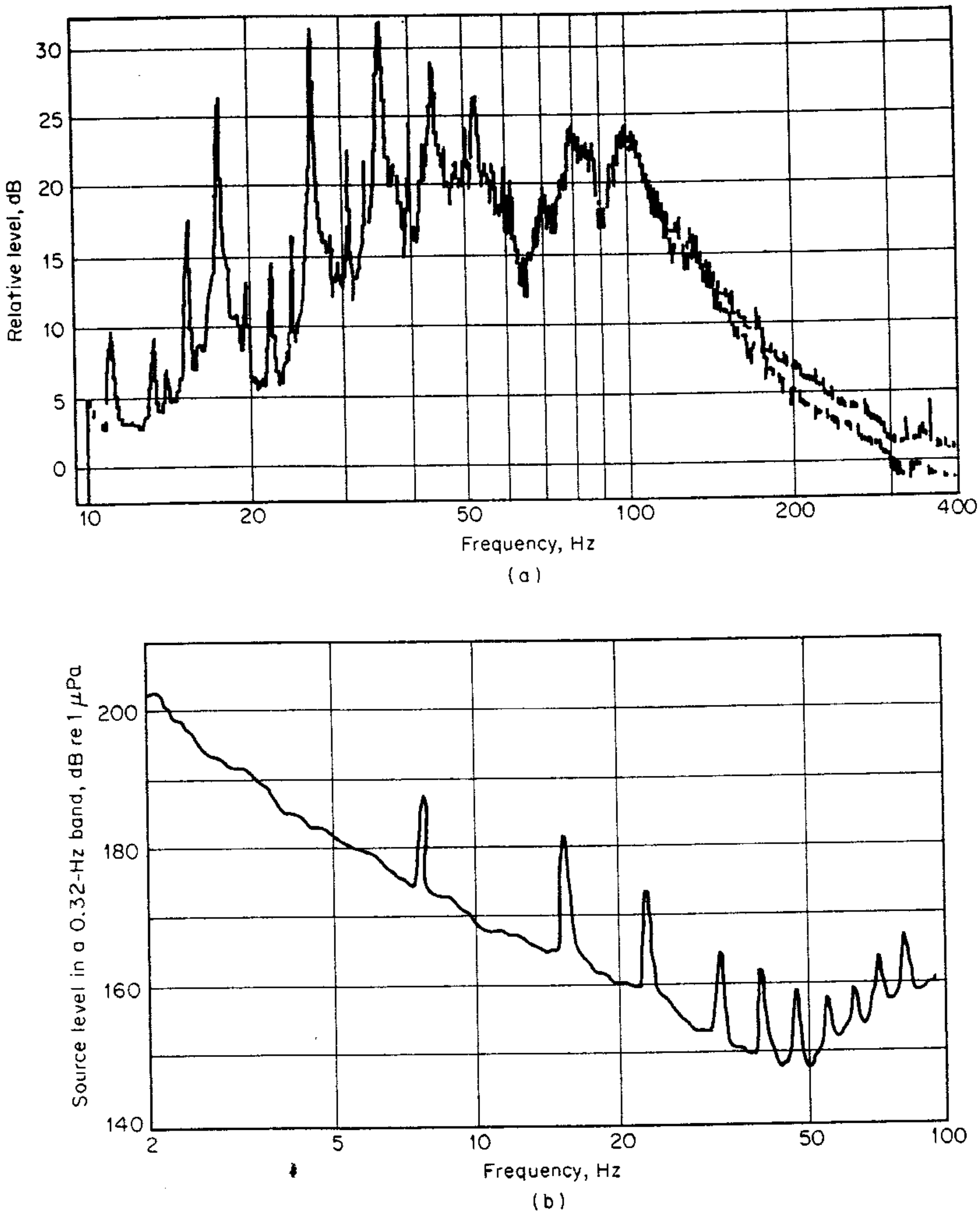


fig. **10.11** *Narrow-band spectra of two merchant ships. (a) A bulk cargo ship, deadweight tons 12,200, speed 14.7 knots, analysis bandwidth 0.1 Hz. (b) A supertanker, "World Dignity," deadweight tons 271,000, speed 16 knots, shaft rate 1.44 rps, number of propeller blades 5, analysis bandwidth 0.32 Hz. (Ref. 7.)*

line components are evenly spaced at 8-Hz intervals, although they do not appear to be so because of the logarithmic frequency scale.

The emission of air around the propeller is an effective practical way of reducing propeller noise. When cavitation occurs, air bubbles emitted in the neighborhood of the cavitating propeller replace the water-vapor bubbles created by the physical rupture of the water. The bubbles of air collapse with less force and thereby soften the effect of collapse caused by cavitation.

Hydrodynamic noise Hydrodynamic noise originates in the irregular and fluctuating flow of fluid past the moving vessel. The pressure fluctuations associated with the irregular flow may be radiated directly as sound to a distance, or, more importantly, may excite portions of the vessel into vibration. The noise created by the turbulent boundary layer is sometimes called "flow noise."

The excitation and reradiation of sound by various structures of the vessel are an important source of hydrodynamic noise. One kind of such noise is propeller singing, mentioned above. In addition, the flow of fluid may have an "aeolian harp" effect on other structures of the vessel, such as struts, and excite them into a vibrational resonance. Like Helmholtz resonators, cavities may be excited by the fluid flow across their openings, in the manner that a bottle can be made to "sing" by blowing over its opening. These resonant occurrences can sometimes be easily diagnosed and curative measures applied.

The form of hydrodynamic noise called *flow noise* is a normal characteristic of flow of a viscous fluid and occurs in connection with smooth bodies without protuberances or cavities. Flow noise can be radiated directly or indirectly as flow-induced vibrations of plates or portions of the body. The former—direct radiation to a distance—is an inefficient process not likely to be important at the low Mach numbers (ratio of speed of the vessel to the speed of sound in water) reached by vessels moving through water, since it is of quadrupole origin and is therefore not efficiently radiated to a distance. The latter process—flow excitation of a nonrigid body—depends on (1) the properties of the pressure fluctuation in the turbulent boundary layer, (2) the local response of the structure to these fluctuations, and (3) the radiation of sound by the vibrating portion. The response of plates to a random pressure field has been studied theoretically by Dyer (12). Flow noise is a more important contribution to self-noise than to radiated noise, and will be discussed more fully as a part of self-noise.

Other kinds of hydrodynamic noise are the roar of the breaking bow and stern waves of a moving vessel and the noise originating at the intake and exhaust of the main circulating water system.

Under normal circumstances, hydrodynamic noise is likely to be only a minor contributor to radiated noise, and is apt to be masked by machinery and propeller noises. However, under exceptional conditions, such as when a structural member or cavity is excited into a resonant source of line-component noise, hydrodynamic noise becomes a dominant noise source in the region of the spectrum in which it occurs.

10.4 Summary of the Sources of Radiated Noise

Of the three major classes of noise just described, machinery noise and propeller noise dominate the spectra of radiated noise under most conditions. The relative importance of the two depend upon frequency, speed, and depth.

This is illustrated by Fig. 10.12 which shows the characteristics of the spectrum of submarine noise at two speeds. Figure 10.12*a* is a diagrammatic spectrum at a speed when propeller cavitation has just begun to appear. The low-frequency end of the spectrum is dominated by machinery lines, together with the blade-rate lines of the propeller. These lines die away irregularly with increasing frequency and become submerged in the continuous spectrum of propeller noise. Sometimes, as indicated by the dotted line, an isolated high-frequency line or group of lines appear amid the continuous background of propeller noise. These high-frequency lines result from a singing propeller or from particularly noisy reduction gears, if the vessel is so equipped.

At a higher speed (Fig. 10.12*b*), the spectrum of propeller noise increases and shifts to lower frequencies. At the same time, some of the line components increase in both level and frequency, whereas others, notably those due to auxiliary machinery running at constant speed, remain unaffected by an increase in ship speed. Thus, at the higher speeds, the continuous spectrum of propeller cavitation overwhelms many of the line components and increases its dominance over the spectrum. A *decrease* in depth at a constant speed has, as indicated above, the same general effect on the propeller-noise spectrum as an *increase* in speed at constant depth.

For a given speed and depth, therefore, a "crossover" frequency may be said to exist, below which the spectrum is dominated by the line components of the ship's machinery plus its propeller, and above which the spectrum is in large part the continuous noise of the cavitating propeller. For ships and submarines, this frequency lies roughly between 100 and 1,000 Hz, depending on the individual ship and its speed and depth; for torpedoes, the crossover frequency is higher and the line components extend to higher frequencies because of the generally higher speeds of operation of torpedo machinery.

For illustrating the nature of ship spectra, a frequency-time analyzer, such as that used for speech analysis, is particularly convenient. This kind of analyzer, called a sound spectrograph, was first described by Koenig, Dunn, and

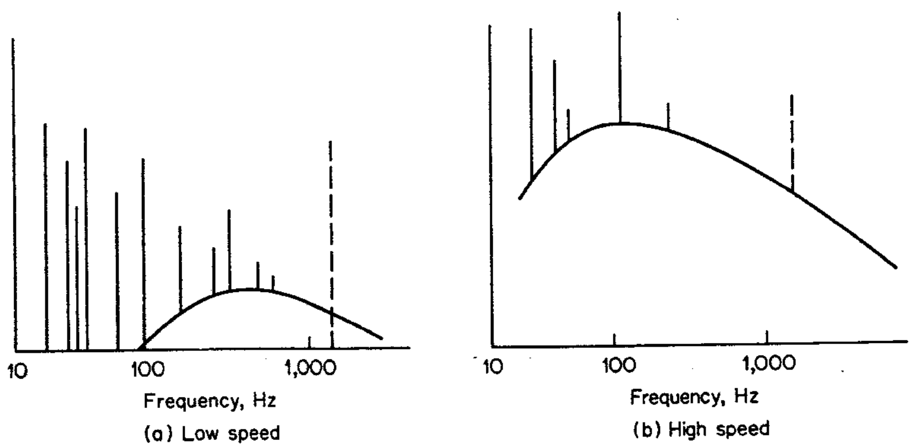


fig. 10.12 Diagrammatic spectra of submarine noise at two speeds.

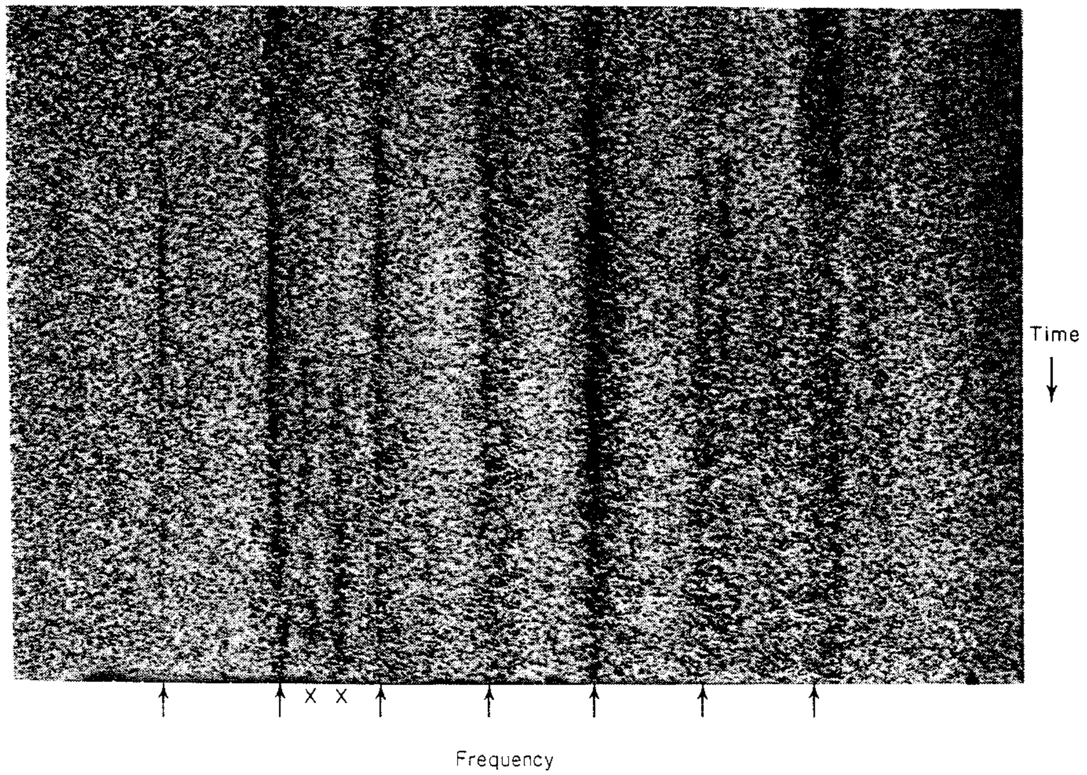


fig. **10.13** *Sound spectrogram of a surface ship at a speed of 11 knots.*

Lacy (13) and is widely used for the analysis of speech (14). It gives a plot of frequency against time and shows the intensity of the sound in the analysis bandwidth by a darkening of the record. Figure 10.13 is an example of a sound spectrogram of the noise of a large surface ship as it passed over a deep hydrophone. The frequency scale extends from 0 to 150 Hz, and the duration of the recording was approximately ½ hour. The harmonic series of line components marked by the arrows are blade-rate lines. The lines marked X are of unknown origin.

An interesting recent observation is that the noise spectrum of fishing boats, when trolling for fish at a speed of 10 to 12 knots, apparently influences the size of their catch of fish. Boats having spectral peaks above 1,500 Hz in their noise radiation were found to have an appreciably smaller catch of albacore than similar boats fishing at the same time and location, but having no strong high-frequency radiation, as if the high-frequency tones were scaring away, rather than luring, this particular species of fish (15).

10.5 Total Radiated Acoustic Power

It is of interest to determine how much total acoustic power is radiated by a moving vessel and how it compares with the power used by the vessel for propulsion through the water. This can easily be done by integration of the spectrum. When the spectrum is continuous and has a slope of −6 dB/octave, the intensity dI in a small frequency band df centered at frequency f can be written as

$$dI = \frac{A}{f^2}\,df$$

where $1/f^2$ represents the -6 dB/octave slope of the spectrum and A is a constant.

By integrating between any two frequencies f_1 and f_2, the total intensity between f_1 and f_2 becomes

$$I_{(f_1,f_2)} = \int_{f_1}^{f_2} \frac{A}{f^2}\,df = A\left(\frac{1}{f_1} - \frac{1}{f_2}\right)$$

Letting $f_2 \rightarrow \infty$, we find that the total intensity for all frequencies above f_1 is

$$I_{tot} = \frac{A}{f_1}$$

Recognizing that A/f_1^2 is the intensity in a 1-Hz band centered at frequency f_1, we note that

$$I_{tot} = (I_{f1})(f_1)$$

where $10 \log I_{f1}$ is the spectrum level at f_1.

As an example (Fig. 10.14), we take a spectrum having a spectrum level of 160 dB at 200 Hz with slope of $1/f^2$ above this frequency. The total level of the radiated noise above 200 Hz becomes

$$\begin{aligned} 10 \log I_{tot} &= 10 \log I_{f1} + 10 \log f_1 \\ &= 160 + 23 = 183 \text{ dB} \end{aligned}$$

The total acoustic power represented by this source level, if assumed to be radiated nondirectionally, amounts to 12 watts. It may be observed that if the continuous spectrum extended below 200 Hz to zero Hz at the constant level of 160 dB, as shown by the dashed line in Fig. 10.14, the total radiated power

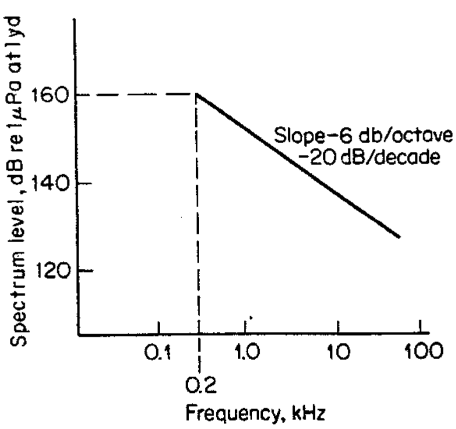


fig. 10.14 Idealized spectrum integrated to obtain the total acoustic power radiated by a vessel.

at frequencies *below* 200 Hz would also be 12 watts, and the total radiation over the entire spectrum would become 24 watts.

If the vessel is regarded as a mechanical source of sound, this radiated power may be compared with the shaft horsepower developed by the radiating vessel. Let us assume that the selected spectrum corresponds to that of a destroyer at a speed of 20 knots. At this speed, an average destroyer is known to generate a shaft horsepower of approximately 14,000, or about 10^7 watts. Comparing this power with that radiated as sound in the continuous part of the spectrum, we observe that the efficiency of the vessel as a sound producer is only of the order of 10^{-6}. Surface ships are therefore extremely inefficient radiators of sound in terms of the developed shaft power of their propulsion system, even when allowance is made for the power represented by the tonal components of the radiation.

10.6 Radiated-Noise Levels

During World War II, the United States and Great Britain, motivated by the design needs of acoustic mines, made a great many measurements of the radiated noise of surface ships at a number of acoustic ranges. At locations such as Wolf Trap, Virginia; Treasure Island, California; Thames River, New London, Connecticut; Puget Sound, Washington; and Waipio Point, Honolulu, Hawaii, literally thousands of "runs" on hundreds of ships of all types were made. Far fewer wartime measurements were made on submarines and torpedoes. Although much of this old data is obsolete because many of the vessels measured are no longer in existence, the general run of sound levels and their variation with speed, frequency, and depth will still be pertinent to many presently existing vessels, if only as a guide for approximation.

In the following sections, a few extracts have been selected from this vast wartime literature to illustrate the main quantitative aspects of the subject. Particular attention is called to two excellent summaries on the radiated-noise levels of submarines (4) and surface ships (5) and to one of the NDRC Summary Technical Reports (17) on the radiated noise of torpedoes.

Surface ships Table 10.2 shows typical radiated source levels for various classes of ships current during World War II, as reduced to 1 yd from an original reference distance of 20 yd by the conventional assumption of spherical spreading.

In graphical form, Fig. 10.15 gives in the upper set of curves average spectrum levels at 5 kHz as a function of speed for a number of classes of surface ships. The lower curve is a relative spectrum for use in obtaining values at other frequencies. The standard deviation (in decibels) of individual measurements from the line drawn is indicated for each class of ships.

Empirical expressions also were devised to fit the mass of data. In terms of the propeller-tip speed V in feet per second, the displacement tonnage T of

table 10.2 Typical Average Source Levels for Several Classes of Ships in dB vs. 1 μPa in a 1-Hz Band at 1 yd.* (Ref. 5)

Frequency	Freighter, 10 knots	Passenger, 15 knots	Battleship, 20 knots	Cruiser, 20 knots	Destroyer, 20 knots	Corvette, 15 knots
100 Hz	152	162	176	169	163	157
300 Hz	142	152	166	159	153	147
1 kHz	131	141	155	148	142	136
3 kHz	121	131	145	138	132	126
5 kHz	117	127	141	134	128	122
10 kHz	111	121	135	128	122	116
25 kHz	103	113	127	120	114	108

* Originally reported at 20 yd.

the ship, the frequency F in kilohertz, and distance D in yards, the source level for the average radiated noise of large ships was found to be given by

$$\text{SL} = 51 \log V + 15 \log T - 20 \log F + 20 \log D - 13.5$$

This formula, based on 157 runs of 77 ships of 11 different classes (mostly freighters, tankers, and large warships), was found to fit individual measurements to a standard deviation of 5.4 dB. It is applicable only at frequencies above 1 kHz where propeller cavitation is the principal source of noise. A more convenient formula, in terms of the speed of the ship, for use when information concerning the propeller-tip speed is lacking, was found to be

$$\text{SL} = 60 \log K + 9 \log T - 20 \log F + 20 \log D + 35$$

In this formula K is the forward speed of the ship in knots. This expression was found to fit the measured levels of passenger ships, transports, and warships at a frequency of 5 kHz to a standard deviation of 5.5 dB, but to be unreliable for freighters and tankers.

Figure 10.16 shows the radiated noise of a postwar destroyer as a function of speed for three frequencies. World War II levels as read from Fig. 10.15 for 500 and 5,000 Hz are also plotted. The residual levels at speeds less than 10 knots are caused by auxiliary and other non-speed-dependent machinery aboard the vessel.

At the low-frequency end of the spectrum, Fig. 10.17 illustrates other measured data (1) on four destroyers measured in the frequency bands 2 to 17 Hz and 7 to 35 Hz. The levels shown are band levels giving the total intensity measured in each band. The levels of any individual line components in the spectrum would be an indefinite number of decibels higher than the level indicated, depending on the number and relative strengths of the lines occurring in each band.

The distribution of radiated levels in the octave 75 to 150 Hz, based on a large number of ship runs at a number of wartime acoustic ranges (18), is shown in Fig. 10.18. In terms of the spectrum level at 1 yd, the ordinate in this figure gives the percentage of runs in which the measured level exceeded that

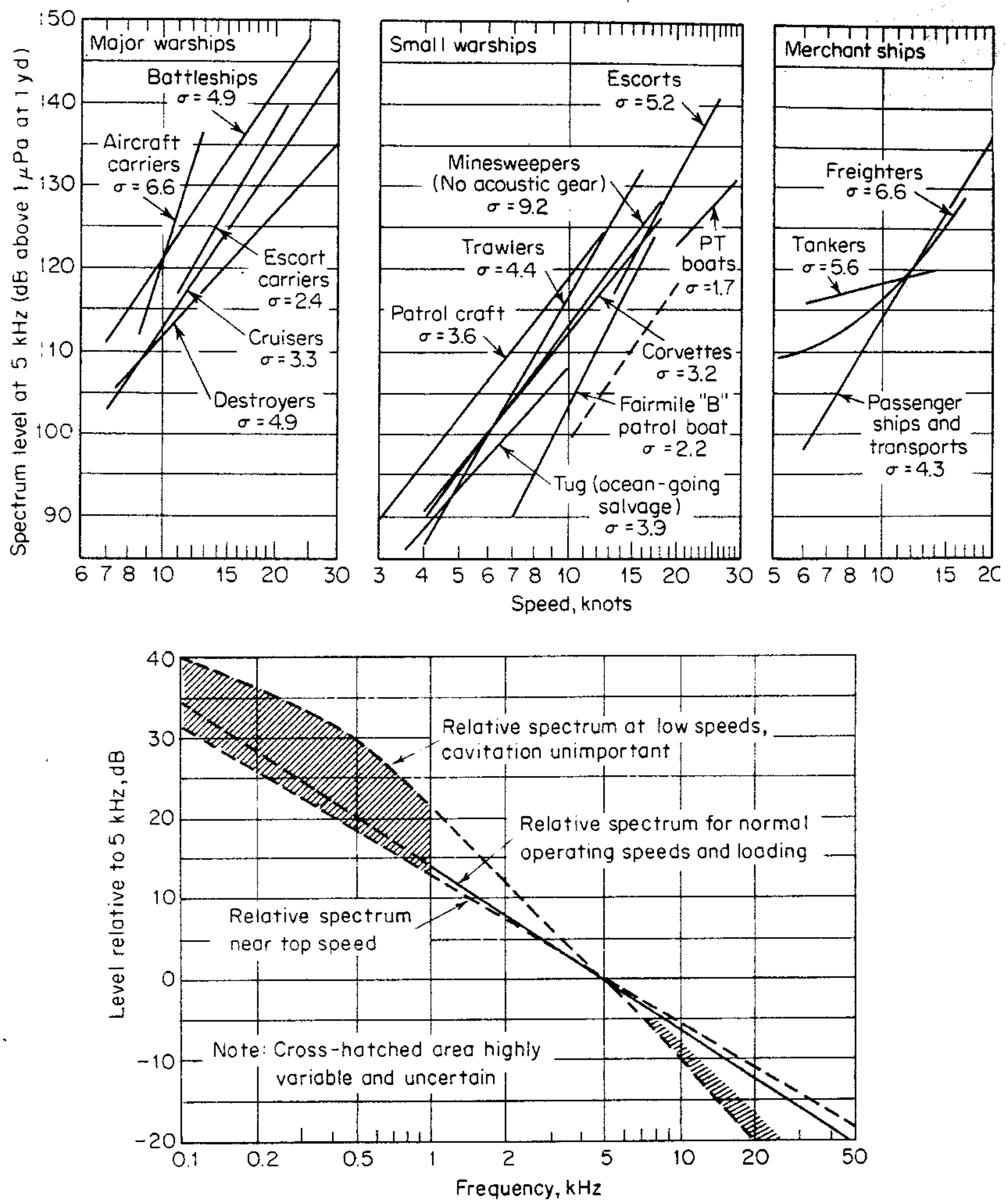


fig. 10.15 *Average radiated spectrum levels for several classes of surface ships. (Ref. 5.)*

shown on the horizontal scale. The levels have been reduced to spectrum levels at 1 yd from octave-band data given at a distance of 100 ft beneath the ship.

Regarding such averaged, reduced data, it should be borne in mind that individual ships occasionally deviate greatly from the average levels. Moreover, at low frequencies, the use of spectrum levels is questionable because of the likely tonal content of the radiated sound. Finally, the data are entirely based on measurements on the bottom in shallow water averaging 20 yd in depth, and do not necessarily indicate the levels that would be observed in deep water.

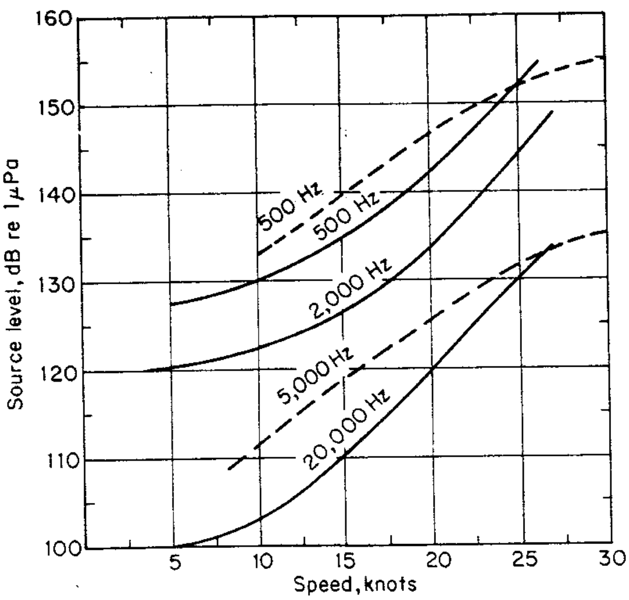


fig. 10.16 *Solid curves, noise level versus speed at 0.5, 2, and 20 kHz for a postwar destroyer. Dashed curves, noise level versus speed for World War II destroyers from Fig. 10.15.*

A quantitative model for the radiation at the blade-rate fundamental frequency has been presented by Gray and Greeley (16). Based on this model, expressions for the source level at the design speed of the blade-rate radiation of merchant ships were found to be

$$
\begin{aligned}
SL_D &= 6 + 70 \log L \pm 11 \text{ dB} \\
&= 92 + 94 \log D \pm 8 \text{ dB}
\end{aligned}
$$

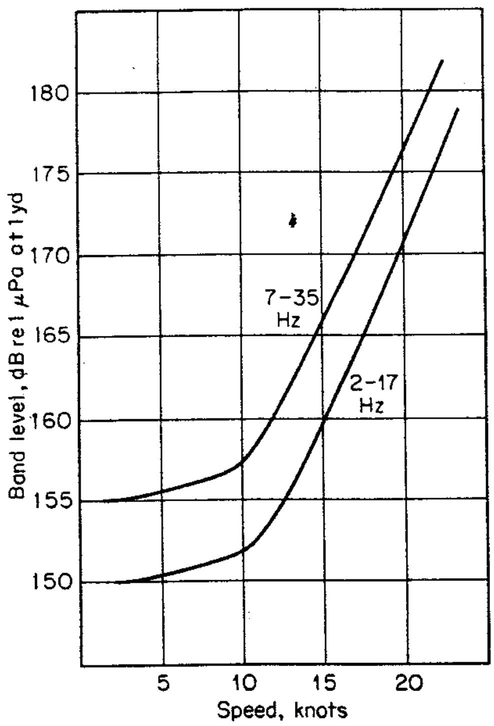
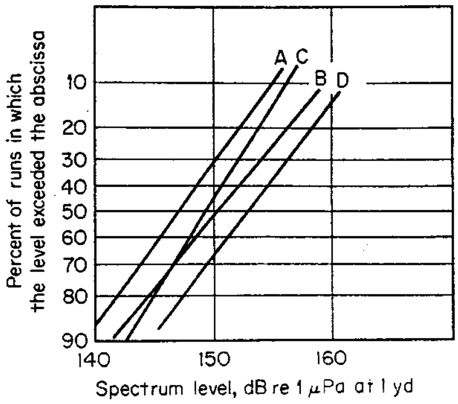


fig. 10.17 *Average levels on four destroyers in two frequency bands as measured on the bottom in 105 ft of water at the Puget Sound acoustic range. Values reduced from 105 ft to 1 yd. (Ref. 1.)*



		Ships	Speed
A	(88 runs)	< 5,000 tons	< 10 knots
B	(132 runs)	< 5,000 tons	≥ 10 knots
C	(72 runs)	> 5,000 tons	< 10 knots
D	(129 runs)	> 5,000 tons	≥ 10 knots

fig. 10.18 *Cumulative distribution curves of the radiated noise of surface ships in the octave 75 to 150 Hz. (Ref. 18.) Horizontal scale is spectrum level obtained from band levels by subtracting 10 log bandwidth and reduced from 100 ft to 1 yd by assuming spherical spreading.*

where L and D are the ship length and propeller blade diameter, both in meters. The uncertainty values of 11 and 8 dB are the estimated standard deviation of a prediction based on these expressions, relative to calculated values based on the model and the known characteristics—such as ship length, draft, and propeller size—of merchant ships. The source level SL_D is the dipole source level at 1 meter. From it, the free-field source level can be found from

$$SL = SL_D + 6 + 20 \log kd$$

where k is the wave number $2\pi/\lambda = 2\pi f/c$, and where d is the operating depth of the propeller. For merchant ships the blade-rate fundamental frequency f falls largely in the range 6.7 to 10.0 Hz, and lies near 8 Hz for many ships. However, no data are available to compare the predictions based on this hydrodynamic model with noise measurements on actual ships under way at sea.

Submarines The available data on submarines are much less extensive and involve only a few submarines under limited operating conditions. Figure 10.19 shows average spectra for three World War II submarines at periscope depth (about 55 ft to the keel) and at the surface. Spectra appreciably higher, though similar in shape, were obtained for the single British submarine, HMS "Graph," as illustrated in Fig. 10.20.

The effect of depth on the radiated levels of submarines is illustrated in Fig. 10.21, which shows the reduction in noise involved in submerging from periscope depth to 200 ft. The effect of depth may also be determined from Fig. 10.8, given previously, in which the spectrum level was plotted as a function of speed divided by the square root and the hydrostatic pressure. These depth

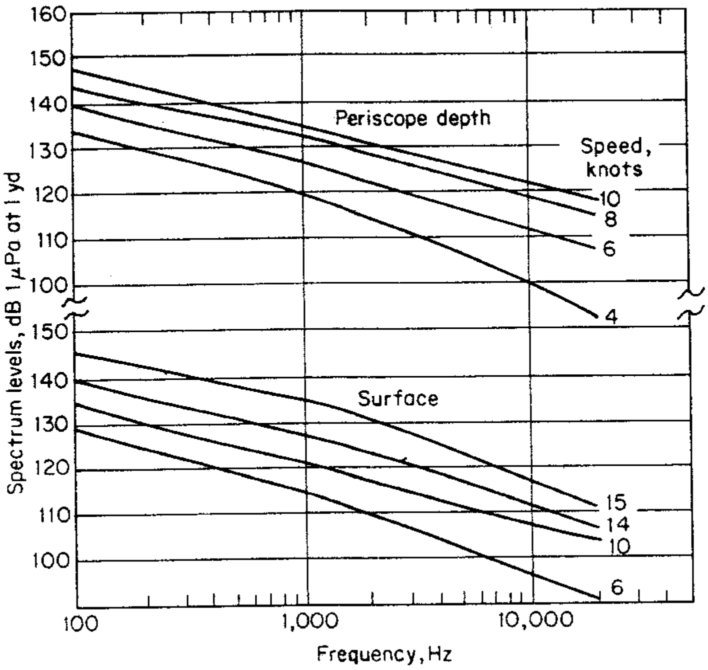


fig. **10.19** *Smoothed spectra of three submaries (USS S-48, "Hake," and "Runner") on electric drive. Levels, originally reported at 200 yd, reduced to 1 yd. (Ref. 4.)*

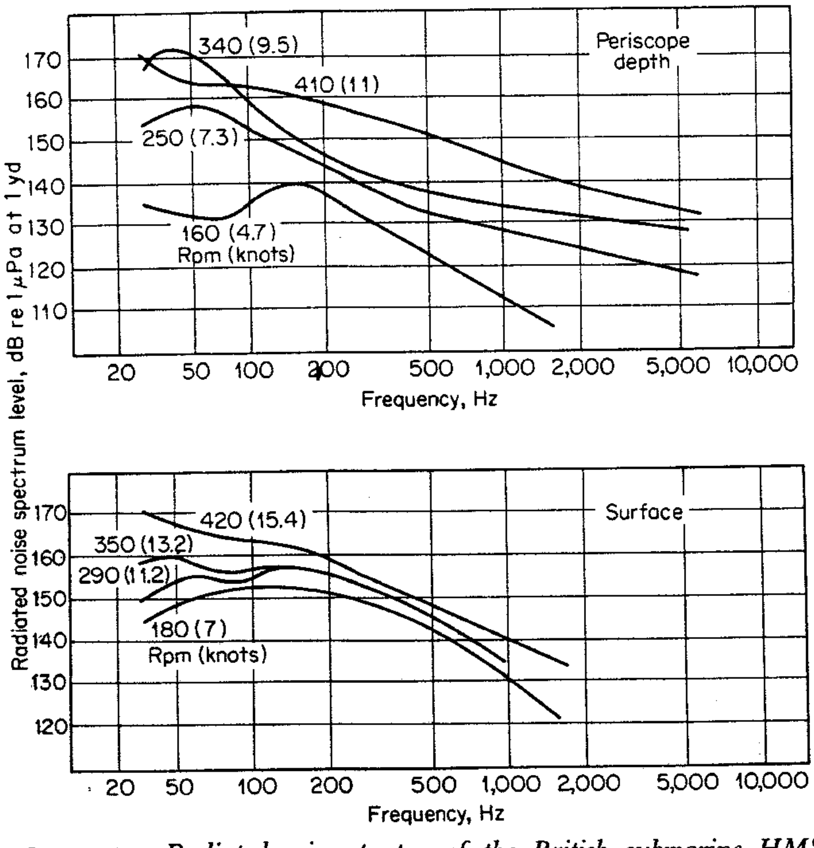


fig. **10.20** *Radiated-noise spectra of the British submarine HMS "Graph" at periscope depth and on the surface. 200-yd reported data reduced to 1 yd. (Ref. 4.)*

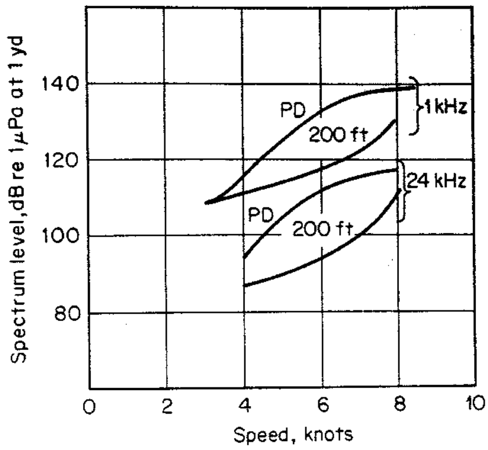


fig. 10.21 *Representative submarine-radiated-noise spectrum levels at two frequencies at periscope depth (PD) and at a depth of 200 ft on electric drive. (Ref. 19.)*

effects occur only for the noise produced by the cavitating propeller; when machinery noise predominates, as at very low speeds or very low frequencies, little or no quieting on submergence to deep depths is expectable.

Torpedoes Figure 10.22 illustrates measured radiated-noise spectra over a wide frequency range for a variety of torpedoes running at different speeds, and Fig. 10.23 is a compilation of torpedo noise levels at 25 kHz as a function of speed. Although the torpedoes listed had a variety of propulsion systems, the noise radiated at kilohertz frequencies must be presumed to be dominated by propeller cavitation.

10.7 *Cautionary Remark*

The potential user of the numerical data presented in this chapter will discover that it represents, for the most part, World War II measurements on obsolete vessels. Although it may be useful for first-cut problem solving and for showing qualitative effects, it must be stressed that the source level data will be almost useless for practical work. The subject of the radiated noise of

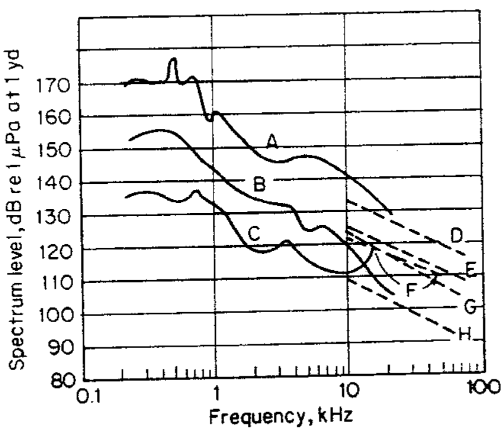


fig. 10.22 *Noise spectra of various World War II torpedoes running at shallow depths. [(A–C), Ref. 20; (D–H), Ref. 17.] (A) Highest measured values for several U.S. torpedoes. (B) Japanese Mark 91, 30 knots. (C) U.S. Mark 13, 30 knots. (D) U.S. Mark 14, 45 knots. (E) British Mark VIII, 37 knots. (F) U.S. Mark 18, 30 knots. (G) U.S. Mark 13, 33 knots. (H) British Mark VIII, 20 knots.*

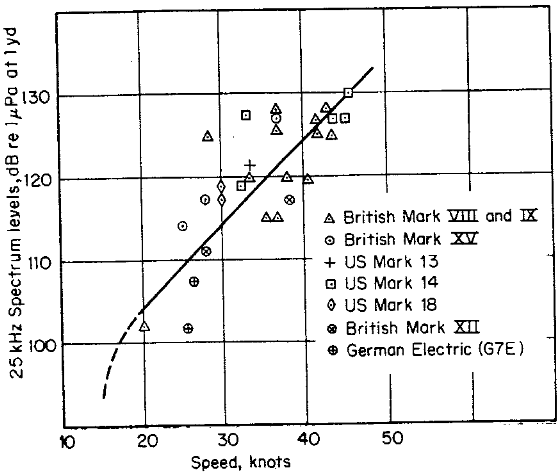


fig. 10.23 *25-kHz spectrum levels of various torpedoes as a function of speed. The straight line has a slope of 1 dB/knot increase of speed.* (*Ref. 17.*)

vessels is, and has long been, almost completely classified on security grounds, and the reader must resort to the classified literature for the information and data needed on modern existing vessels.

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