nine

reflection and scattering by sonar targets: target strength

This chapter is concerned with the subject of *catacoustics*. According to Webster's "New International Dictionary of the English Language," 2d edition, the word "catacoustics" is defined as "that part of acoustics which treats of reflected sounds or echoes."

In active sonar the parameter *target strength* refers to the echo returned by an underwater target. Such targets may be objects of military interest, such as submarines and mines, or they may be schools of fish sought by fish-finding sonars. Excluded from the category of "targets" are inhomogeneities in the sea of indefinite extent, such as scattering layers and the ocean surface and bottom, which, because of their indefinite size, return sound in the form of *reverberation* instead of as *echoes*.

In the context of the sonar equations, target strength is defined as 10 times the logarithm to the base 10 of the ratio of the intensity of the sound returned by the target, at a distance of 1 yd from its "acoustic center" in some direction, to the incident intensity from a distant source. In symbols,

$$\mathrm{TS} \equiv 10 \log \left.\frac{I_r}{I_i}\right|_{r=1}$$

where I_r = intensity of return at 1 yd
I_i = incident intensity

Pictorially this is shown in Fig. 9.1, where P is the point at which I_r is imagined to be measured and C is the acoustic center of the target. This fictitious point,

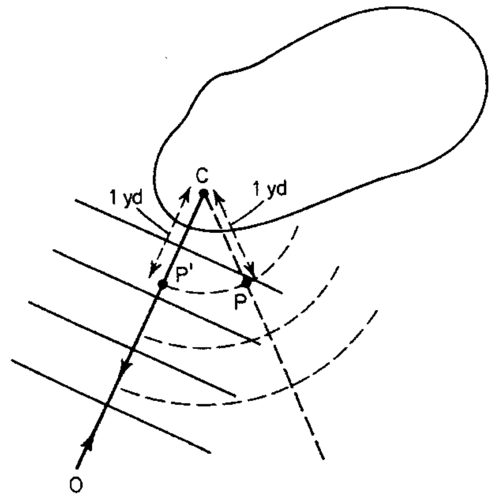

fig. **9.1** *Geometry of target strength. A plane wave is incident on the target in the direction OC. Target strength refers to the points P and P' 1 yd from the acoustic center C.*

inside or outside of the target itself, is the point from which the returned sound appears to originate on the basis of measurements made at a distance. In "monostatic" sonars, having the same, or closely adjacent source and receiver, the point P lies in the direction back toward the source of sound. In "bistatic" sonars, P can lie in any direction relative to the target, and target strength then becomes a function of both the incident direction and the direction of the receiver, both relative to some axis of symmetry of the target. Because most sonars are "monostatic," we will restrict most of our discussion to "back reflection" and "backscattering," in which the reference point lies at P' back in the direction of the incident sound.

Target strength measurements are always at a long range—that is, in the "far field" (Fig. 4.2)—where the target reradiates as a point source of sound. This virtual point souce is the acoustic center C.

Special mention should be made of the use of 1 yd as the reference distance for target strength. This arbitrary reference often causes many underwater objects to have *positive* values of target strength. Such positive values should not be interpreted as meaning that more sound is coming back from the target than is incident upon it; rather, they should be regarded as a consequence of the arbitrary reference distance. If, instead of 1 yd, 1 kyd was used, all customary targets would have a negative target strength. In metric units of length, where 1 meter is the reference distance instead of 1 yd, all target-strength values are *lower* by the amount 20 log 1.0936 or 0.78 dB; in other words, when a 1-meter reference distance is used, all target-strength values referred to 1 yd must be *reduced* by 0.78 dB.

The meaning of target strength can be shown by computing the target strength of a sphere, large compared to a wavelength, on the assumption that the sphere is an isotropic reflector; that is, it distributes its echo equally in all directions. Let a large, perfect, rigid sphere (Fig. 9.2) be insonified by a plane wave of sound of intensity I_i. If the sphere is of radius a, the power intercepted by it from the incident wave will be $\pi a^2 I_i$. On the assumption that the sphere reflects this power uniformly in all directions, the intensity of the reflected wave at a distance r yards from the sphere will be the ratio of this power to the area of a sphere of radius r, or

$$I_r = \frac{\pi a^2 I_i}{4\pi r^2} = I_i \frac{a^2}{4r^2}$$

where I_r is the intensity of the reflection at range r. At the reference distance of 1 yd, the ratio of the reflected intensity I_r to the incident intensity is

$$\left.\frac{I_r}{I_i}\right|_{r=1} = \frac{a^2}{4}$$

and the target strength of the sphere becomes

$$\mathrm{TS} \equiv 10 \log \left.\frac{I_r}{I_i}\right|_{r=1} = 10 \log \frac{a^2}{4}$$

It is therefore evident that an ideal sphere of radius 2 yd ($a = 2$) has a target strength of 0 dB. In practical work, spheres make good reference targets for sonar when they can be used, because their target strengths are relatively independent of orientation.

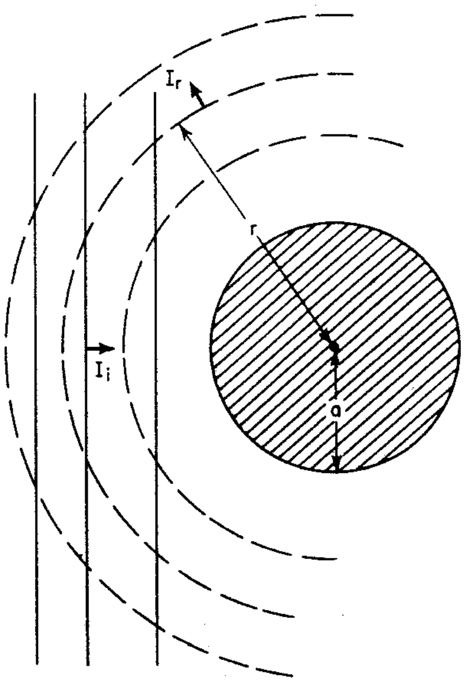

fig. 9.2 A sphere as an isotropic reflector of an incident plane wave.

9.1 The Echo as the Sum of Backscattered Contributions

For radar it was shown by Kerr (1) that the backscattering cross section of a radar target in integral form is

$$\sigma = \frac{4\pi}{\lambda^2} \left| \int_\alpha^\beta \frac{dA}{dz} e^{2ikz} \, dz \right|^2$$

where σ = ratio of scattered power to incident intensity
dA/dz = rate of change of cross-sectional area of body in direction of propagation z
k = wave number $2\pi/\lambda$
λ = incident wavelength
$z = \alpha$, $z = \beta$ are the range limits of the target

The return of an incident plane wave from the target can therefore be regarded as the sum of many wavelets, each originating at the changes in cross-sectional area of the target and added with respect to phase. The application of this expression to sonar is restricted to targets that are large, rigid, and immovable in the sound field, that is, to large targets that do not deform or move under the impact of the incident sound wave.

A thorough application of this approach to the backscattering of underwater sound targets has been made by Freedman (2). In his notation

$$\text{TS} = 10 \log |J|^2$$

where

$$J = \frac{1}{\lambda} \sum_{g=1} e^{-2ik(r_g - r_1)} \sum_{n=0}^{\infty} \frac{D_g^n(A)}{(2ik)^n}$$

and where the symbol $D_g^n(A)$ denotes the magnitude of the discontinuity of the nth derivative of the cross-sectional area of the object at range r_g, and r_1 is the range of the closest point of the target. The target-strength factor J is thus proportional to the sum of all the discontinuities of the derivatives of the cross-sectional area A of the object, measured at some range $r_g - r_1$ from the point nearest the source, weighted by the factor $1/(2ik)^n$, and then summed over all points of the object after allowance for phase by means of the factor $e^{-2ik(r_g - r_1)}$. Freedman also showed experimentally that echo envelopes can be predicted from the various contributions of the derivatives of the cross-sectional-area function occurring at times corresponding to the location of the cross sections along the object in the direction of propagation. A summation method for finding the reflection from irregular bodies has also been the subject of a paper by Neubauer (3).

Figure 9.3, taken from Freedman's work, shows the wave theory echo from a sphere, where each discontinuity in the derivatives give rise to a component of the echo. Wave theory yields a diffracted echo from the edge of the geometrical shadow in addition to the echo from the front of the sphere.

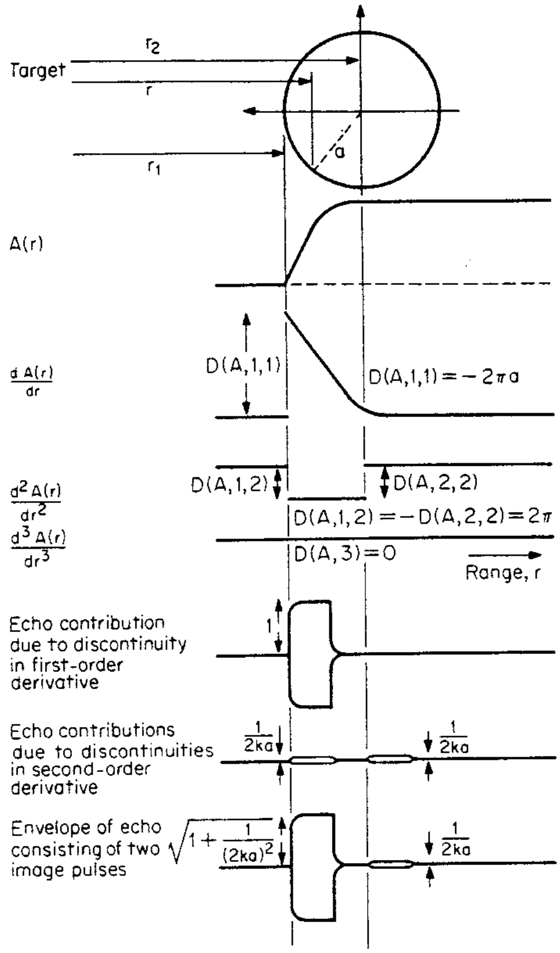

fig. 9.3 *Wave theory origin of the echo from a sphere. The echo is made up of contributions from the discontinuities in the derivatives of the cross-sectional area of the sphere. The theory applies only to objects that are smooth, large compared to* λ, *immovable, nondeformable, and impenetrable to sound. (Ref. 2.)*

9.2 *Geometry of Specular Reflection*

For objects of radii of curvature large compared to a wavelength, the echo originates principally by *specular reflection,* in which those portions of the target in the neighborhood of the point at which sound is normally incident give rise to a coherent reflected echo. One way to find the magnitude of the specular reflection is to construct Fresnel, or quarter-wave zones, on the surface of the body and to add their contributions, as has been done for underwater targets by Steinberger (4). A heuristic intuitive approach is to consider target strength as a measure of the spreading of an incident plane wave induced by specular reflection from a curved surface. If the power or energy-density contained within a small area A_i of the incident sound beam is spread, on reflection, over the area A_r at unit distance, then the target strength is 10 log (A_i/A_r). These areas can be determined by drawing rays. This geometric view of specular reflection will be illustrated by computing the target strength of a sphere and a general convex surface, both satisfying the requirement of large radii of curvature compared to a wavelength.

Figure 9.4 shows a perfect, large rigid sphere with a plane sound wave incident from the left. Adjacent incident rays intersect along the curve *OQO′*,

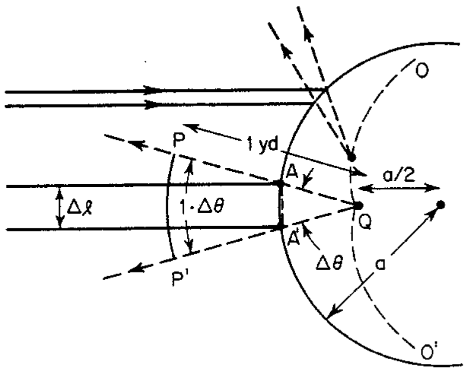

fig. 9.4 Target strength of a sphere. The acoustic energy contained in the pencil of diameter Δl is spread on reflection over a portion PP' of a 1-yd sphere.

having a cusp at Q halfway from the surface to the center of the sphere. This *caustic* is the locus of the acoustic centers of the adjacent intersecting rays. Consider a small cylindrical bundle of parallel rays normally incident upon the sphere at AA' and of cross section Δl. If the intensity of the incident wave is I_i, the power contained in the bundle is $I_i\pi(\Delta l)^2/4$. This power will, in effect, be reradiated within an angle $\Delta\theta$ from the acoustic center Q for these rays. At unit distance from Q, this power is distributed over a portion of a sphere PP' of area $\pi(\Delta\theta \times 1)^2/4$ if $\Delta\theta$ is small, and the intensity there becomes

$$I_r = \frac{I_i\pi(\Delta l)^2/4}{\pi(\Delta\theta \times 1)^2/4} = I_i\left(\frac{\Delta l}{\Delta\theta}\right)^2$$

But, referring to the triangle AQA', it will be seen that

$$AA' = \Delta l = \frac{a}{2}\Delta\theta$$

for small $\Delta\theta$. Hence $\Delta l/\Delta\theta = a/2$ and

$$\text{TS} \equiv 10\log\frac{I_r}{I_i}\bigg|_{r=1} = 10\log\frac{a^2}{4}$$

This is the same as before, and indicates that a large sphere reflects the incident plane wave in the backward direction *as though* it were a uniform, or isotropic, reflector of sound. For this simple expression to hold strictly, distances must be reckoned from the acoustic center of the sphere located halfway from the surface to the center. For practical purposes in sonar, where ranges much greater than the radius of the sphere are involved, the exact location of the acoustic center is not usually significant. It should be observed that we have considered a sphere that is (1) *perfect* in shape, without irregularities, depressions, or protuberances, (2) *rigid,* or nondeformable by the impinging sound beam, (3) *immovable,* or does not partake of the acoustic motion of the field in which it is embedded, and (4) *large* compared to a wavelength ($2\pi a/\lambda \gg 1$).

This same method can be extended to the reflection at normal incidence from any convex surface having all radii of curvature large compared to a wavelength. This requirement carries with it the absence of protuberances, corners, and angles, all of which involve small radii of curvature and which serve as scatterers instead of reflectors of sound. Such a large, smooth, convex object is shown in Fig. 9.5*a*, with sound normally incident at point P along the line OP. Imagine a series of planes through OP intersecting the object. Two of them lie at right angles to each other and intersect the object in the *principal normal sections* having a maximum and a minimum radius of curvature. Figure 9.5*b* is a plan view at P in which the principal normal sections are AA' and BB'; Fig. 9.5*c* is a cross section through AA' in which R_1 is the radius of curvature, O the center of curvature, and Q the acoustic center located halfway from O to P. Consider a small rectangular segment of the surface having one corner located at P, and of infinitesimal lengths dl_1 and dl_2 on each side.

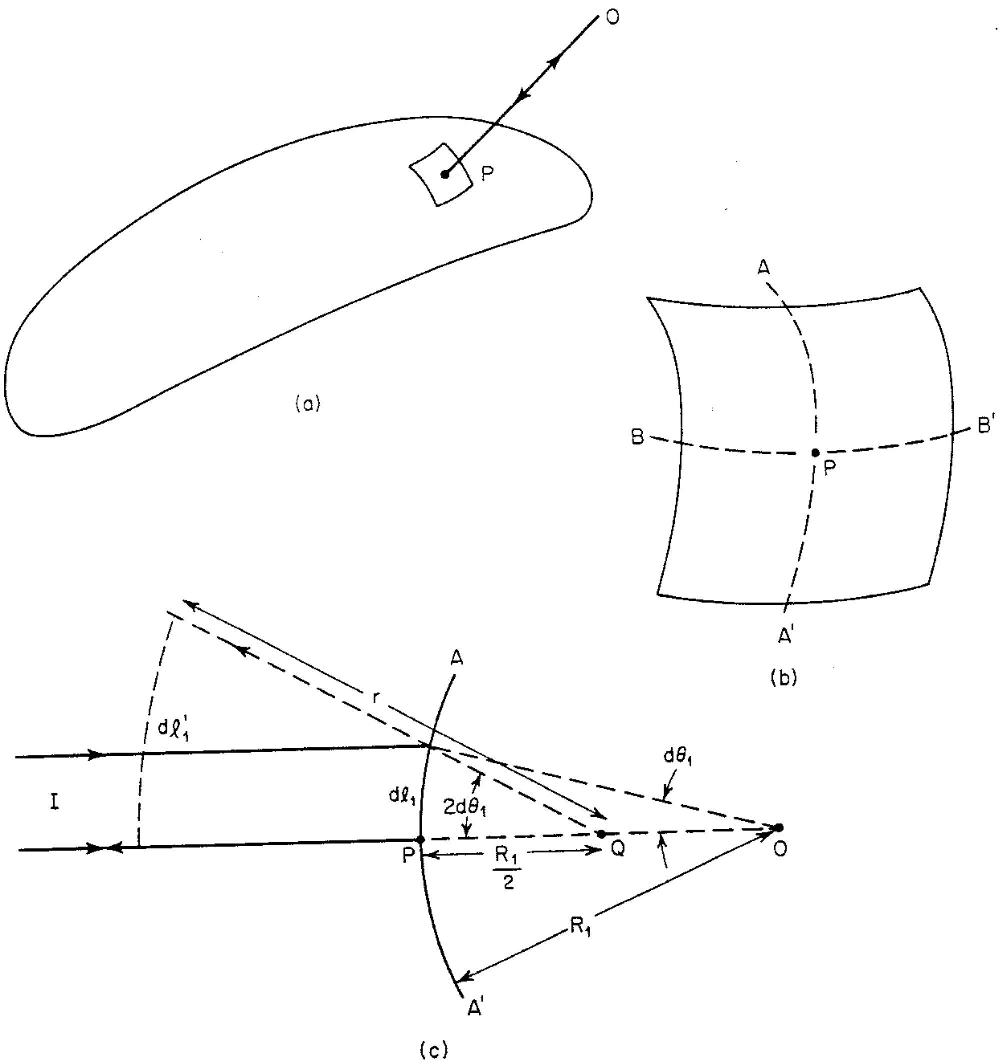

fig. 9.5 *Target strength of a convex target of large radius of curvature: (a) A target with sound normally incident along OP. (b) Plan view of the vicinity of P with AA' and BB' in the principal normal sections. (c) Cross section through AA' of radius of curvature* R_1.

If a plane wave of intensity I_i is incident on the surface, the power dP intercepted by the segment will be

$$dP = I_i \, dl_1 \, dl_2$$

But from the cross section of Fig. 9.5*c*, it is apparent that

$$dl_1 = R_1 \, d\theta_1$$

and similarly in the perpendicular plane containing BB' we would have

$$dl_2 = R_2 \, d\theta_2$$

so that the power intercepted will be

$$dP = I_i R_1 R_2 \, d\theta_1 \, d\theta_2$$

On reflection from the sphere, this power is distributed, at range r from the acoustic center C, over an area

$$dA = dl_1' \, dl_2' = 2r \, d\theta_1 \, 2r \, d\theta_2$$

Hence the intensity at r will be

$$I_r = \frac{dP}{dA} = \frac{I_i R_1 R_2}{4r^2}$$

and the target strength will be

$$\mathrm{TS} \equiv 10 \log \left.\frac{I_r}{I_i}\right|_{r=1} = 10 \log \frac{R_1 R_2}{4}$$

9.3 *Target Strength of a Small Sphere*

We consider now the target strength of a small sphere, in which the return of sound back toward the source is a process of scattering instead of reflection.

The theory of sound scattering by a small, fixed, rigid sphere was first worked out by Rayleigh (5). By *small* is meant a sphere whose ratio of circumference to wavelength is much less than unity ($ka = 2\pi a/\lambda \ll 1$); by *fixed*, a sphere that does not partake of the acoustic motion of particles of the fluid in which the sphere is embedded; by *rigid*, a sphere that is nondeformable by the incident acoustic waves and into which the sound field does not penetrate. Under these conditions, Rayleigh showed that the ratio of the scattered intensity I_r at a large distance r to the intensity I_i of the incident phase wave is

$$\frac{I_r}{I_i} = \frac{\pi^2 T^2}{r^2 \lambda^4} \left(1 + \frac{3}{2}\mu\right)^2$$

where T = volume of sphere ($\frac{4}{3}\pi a^3$)
λ = wavelength
μ = cosine of angle between scattering direction and reverse direction of incident wave

For backscattering $\mu = +1$. On reducing to $r = 1$ and on taking 10 times the logarithm, we obtain

$$\text{TS} \equiv 10 \log \frac{I_r}{I_i}\bigg|_{r=1} = 10 \log \frac{\pi^2 T^2}{\lambda^4} \left(\frac{5}{2}\right)^2 = 10 \log \left[(1{,}082) \frac{a^6}{\lambda^4} \right]$$

where a and λ are in units of yards. Thus, the target strength of a small sphere varies as the sixth power of the radius and inversely as the fourth power of the wavelength.

If we define the backscattering cross section of the sphere as

$$\sigma \equiv 4\pi \frac{I_r}{I_i}\bigg|_{r=1}$$

the ratio of backscattering cross section to geometric cross section becomes

$$\frac{\sigma}{\pi a^2} = 2.8(ka)^4$$

Figure 9.6 is a plot of this normalized ratio against the nondimensional quantity $ka = 2\pi a/\lambda$. It is seen that this quantity varies as the fourth power of ka, or as the fourth power of the frequency, for ka less than about 0.5, and is unity for ka greater than 5.0. Oscillations occur in the intermediate region ($ka \approx 1$).

Rayleigh also dealt with the scattering by small spheres, not fixed and rigid, but possessing a compressibility κ' and a density ρ' in a fluid of compressibility κ and density ρ. Fixed, rigid spheres are incompressible ($\kappa'/\kappa \ll 1$) and very dense ($\rho'/\rho \gg 1$) compared to the surrounding fluid; spheres having bulk moduli and densities comparable with those of the fluid oscillate to and fro in

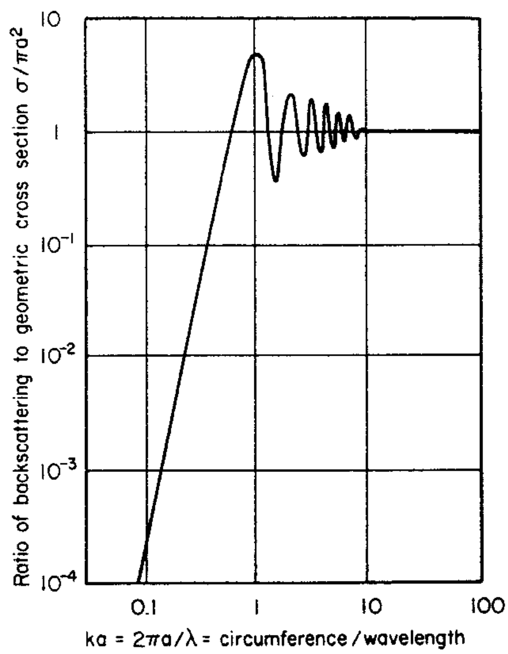

fig. 9.6 *Ratio of acoustic to geometric cross sections of a fixed rigid sphere. The oscillations in the range $1 < ka < 10$ are due to interference by the creeping wave. For small ka (low frequencies) the ratio varies as the fourth power of ka; for large ka the ratio is unity.*

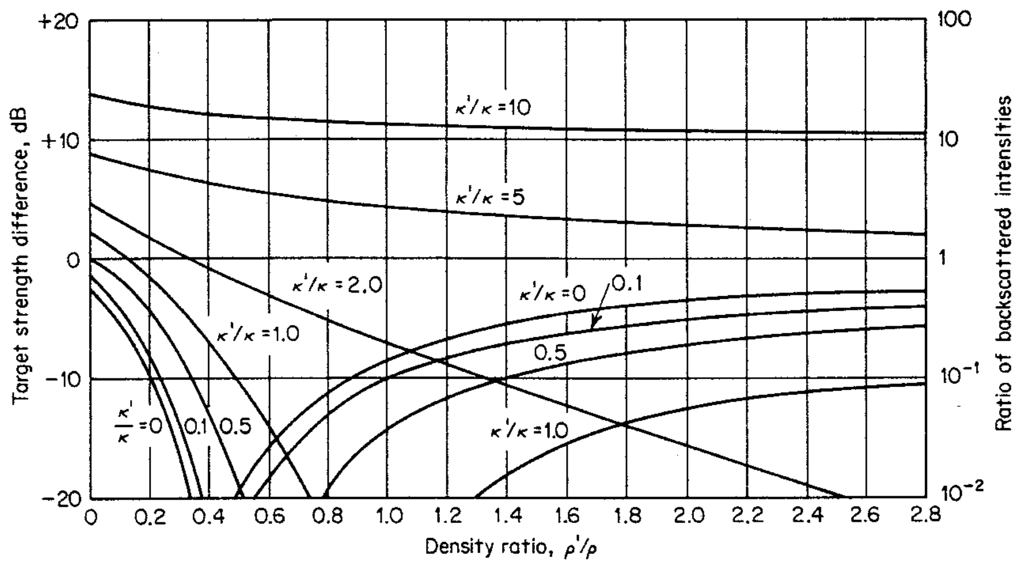

fig. 9.7 *Corrections to the target strength of a fixed rigid sphere for compressibility and density. The sphere is of compressibility ratio* κ'/κ *and density ratio* ρ'/ρ *relative to the surrounding fluid.*

the incident sound field. They also pulsate, or change their volume, in the compressions and rarefactions of the incident wave. These motions of the sphere modify the scattered wave. Rayleigh showed (6) that the term $(1 + \frac{3}{2}\mu)^2$ in the expression for the ratio of intensities for a fixed, rigid sphere becomes

$$\left[1 - \frac{\kappa'}{\kappa} + \frac{3(\rho'/\rho - 1)}{1 + 2\rho'/\rho}\,\mu\right]^2$$

in terms of the ratios of compressibility κ'/κ and density ρ'/ρ. Figure 9.7 is a plot of the quantity

$$10 \log \left[1 - \frac{\kappa'}{\kappa} + \frac{3(\rho'/\rho - 1)}{1 + 2\rho'/\rho}\,\mu\right]^2 \Big/ \left(1 + \frac{3}{2}\mu\right)^2$$

This is the "correction" for compressibility and density to be applied to the target strength of a fixed, rigid sphere. This correction is seen from Fig. 9.7 to be large in most instances. For a sand grain in water, for example, for which $\rho'/\rho = 2.6$ and $\kappa'/\kappa \approx 0.1$, the target strength is seen to be 4 dB less than for the classic Rayleigh case of a fixed, rigid sphere. On the other hand, highly compressible spheres such as gas bubbles in water have enormously greater target strengths, even in the absence of resonance effects. For example, for a nonresonant air bubble in water at 1 atm, κ'/κ is approximately 19,000, and its backscattering is some 77 dB greater than that for classic Rayleigh scattering by a sphere of the same size.

A thorough theoretical treatment of sound scattering from a fluid sphere is given in a paper by Anderson (7).

9.4 Complications for a Large Smooth Solid Sphere

When a sound wave impinges on a large, smooth solid sphere in water, the sphere does not remain inert, but reacts to the impinging wave in different ways. First, sound can enter the sphere as a compressional wave and be reflected from the back side, so as to produce a secondary echo occurring slightly later than the specularly reflected echo from the front of the sphere. Second, flexural waves can be excited on the surface of the sphere at the place where their wavelength and that of sound in water "match." These waves of deformation travel with their own velocity around the sphere and contribute to the echo in the backward direction. Finally, "creeping" waves predicted by wave theory have been observed experimentally (8, 9). These are diffracted waves that originate at the edge of the geometrical shadow and travel around the sphere with the velocity of sound in water. Both surface and creeping waves reradiate in all directions as they travel around the sphere and in so doing become attenuated. The creeping or diffracted waves are the cause of the oscillations in the backscattering cross-section plot of Fig. 9.6 in the region $1 < ka < 10$.

These waves are illustrated in Fig. 9.8. Although they are somewhat academic, they illustrate some of the complications that can occur in the echo from real sonar targets in water.

The penetration of sound into a sphere can be used to enhance its target strength. Marks and Mikeska (10) filled a thin-wall stainless steel sphere with a mixture of the liquids freon and CCl_4, having a sound velocity 0.56 that of water, and found target strengths higher by 20 dB over the theoretical value

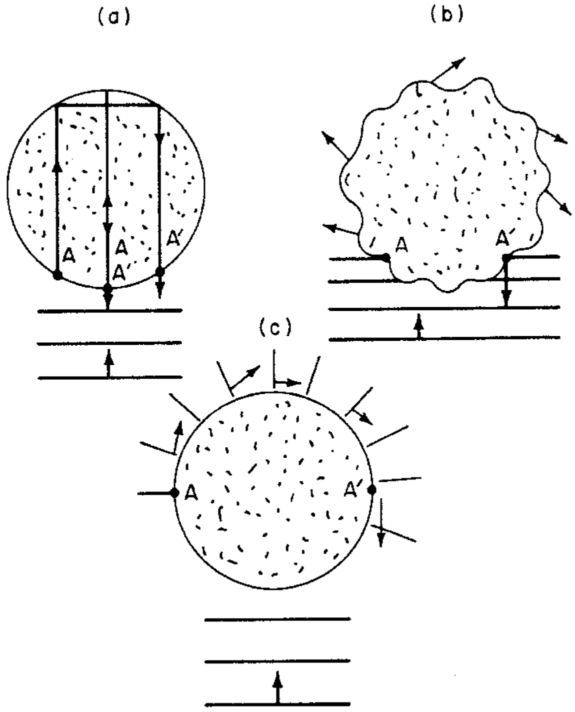

fig. 9.8 Contributions to the echo from a large, smooth solid sphere: (a) Back-reflected compressional waves take one or two bounces off the back side, entering at A and leaving at A'. (b) A flexural surface wave originates at A and leaves at A' reradiating as it travels aorund the sphere. (c) The "creeping" diffracted wave originates at the edge of the shadow boundary and similarly reradiates in all directions.

10 log $a^2/4$ for an impenetrable sphere. In addition, the beamwidth of the returned sound was narrow—about the same as that of a circular piston of the same diameter as the sphere. The filling fluid served to focus the incident sound to the rear of the sphere and thereby produced stronger echoes than would occur if the sphere were either hollow or of solid steel.

9.5 Target Strength of Simple Forms

The target strength of a number of geometric shapes and forms has been found theoretically, in most cases for applications to radar. Table 9.1 presents a list of a number of mathematical forms for which the target strength has been determined, together with the appropriate literature references. These idealized expressions should be viewed as no more than crude approximations for targets of complex internal construction for which penetration and scattering are suspected to occur. Moreover, the mobility and nonrigidity of sonar targets (unlike radar targets) cause them to have target strengths different from what they would have if they were fixed and rigid as theory requires. Yet the expressions will often be found useful for the prediction of the target strength of new and unusual objects for which no measured data are available and which, it is believed, can be approximated well enough by an ideal geometric shape. This use of these expressions will be illustrated later on for mines and torpedoes.

More complex targets can be modeled by breaking them up into elemental parts and replacing each part of one of the various simple forms. For example, a submarine can be modeled by a series of cylinders, wedges, plates, etc., each corresponding to some component of the hull structure. For a long-pulse sonar, the target strength can be found by adding up the contributions of the various simple forms into which the target has been divided. This technique appears to have been successfully employed in radar for estimating the target strength of targets as complex as an approaching jet bomber (11).

9.6 Bistatic Target Strength

Because of the fact that in sonar, as in radar, the monostatic geometry has usually been employed, much less is known about the target strength of underwater objects in the "bistatic" arrangement, that is, when widely separated sources and receivers are used. A rule of thumb assumption that is commonly made is that the target is isotropic: that is, that its target strength is the same in all directions, except possibly in the "glint" directions where specular reflection might exist.

In radar, a method has been found for estimating the bistatic target strength when the monostatic value is known (12). The bistatic theorem states that for large smooth objects, the bistatic target strength is equal to the monostatic target strength, taken at the bisector of "bistatic angle" between the

table 9.1 Target Strength of Simple Forms

Form	t Target strength $= 10 \log t$	Symbols	Direction of incidence	Conditions	References
Any convex surface	$\frac{a_1 a_2}{4}$	$a_1 a_2$ = principal radii of curvature r = range $k = 2\pi$/wavelength	Normal to surface	$ka_1, ka_2 \gg 1$ $r > a$	1
Sphere Large	$\frac{a^2}{4}$	a = radius of sphere	Any	$ka \gg 1$ $r > a$	1
Small	$61.7 \frac{V^2}{\lambda^4}$	V = volume of sphere λ = wavelength	Any	$ka \ll 1$ $kr \gg 1$	2
Cylinder Infinitely long Thick	$\frac{ar}{2}$	a = radius of cylinder	Normal to axis of cy-clinder	$ka \gg 1$ $r > a$	1
Thin	$\frac{9\pi^4 a^4}{\lambda^2} r$	a = radius of cylinder	Normal to axis of cy-clinder	$ka \ll 1$	3
Finite	$aL^2/2\lambda$	L = length of cylinder a = radius of cylinder	Normal to axis of cyl-inder	$ka \gg 1$ $r > L^2/\lambda$	4
	$aL^2/2\lambda(\sin \beta/\beta)^2 \cos^2 \theta$	a = radius of cylinder $\beta = kL \sin \theta$	At angle θ with normal		
Plate Infinite (plane surface)	$\frac{r^2}{4}$		Normal to plane		

table 9.1 Target Strength of Simple Forms (Continued)

Form	t Target strength $= 10 \log t$	Symbols	Direction of incidence	Conditions	References
Finite Any shape	$\left(\frac{A}{\lambda}\right)^2$	A = area of plate L = greatest linear dimension of plate l = smallest linear dimension of plate	Normal to plate	$r > \frac{L^2}{\lambda}$ $kl \gg 1$	5
Rectangular	$\left(\frac{ab}{\lambda}\right)^2 \left(\frac{\sin \beta}{\beta}\right)^2 \cos^2 \theta$	a, b = side of rectangle $\beta = ka \sin \theta$	At angle θ to normal in plane containing side a	$r > \frac{a^2}{\lambda}$ $kb \gg 1$ $a > b$	4
Circular	$\left(\frac{\pi a^2}{\lambda}\right)^2 \left(\frac{2J_1(\beta)}{\beta}\right)^2 \cos^2 \theta$	a = radius of plate $\beta = 2ka \sin \theta$	At angle θ to normal	$r > \frac{a^2}{\lambda}$ $ka \gg 1$	4
Ellipsoid	$\left(\frac{bc}{2a}\right)^2$	a, b, c = semimajor axes of ellipsoid	Parallel to axis of a	$ka, kb, kc \gg 1$ $r \gg a, b, c$	6
Average over all aspects Circular disk	$\frac{a^2}{8}$	a = radius of disk	Average over all directions	$ka \gg 1$ $r > \frac{(2a)^2}{\lambda}$	5
Conical tip	$\left(\frac{\lambda}{8\pi}\right)^2 \tan^4 \psi \left(1 - \frac{\sin^2 \theta}{\cos^2 \psi}\right)^{-3}$	ψ = half angle of cone	At angle θ with axis of cone	$\theta < \psi$	7

table 9.1 Target Strength of Simple Forms (Continued)

Form	t Target strength $= 10 \log t$	Symbols	Direction of incidence	Conditions	References
Any smooth convex object	$\frac{S}{16\pi}$	S = total surface area of object	Average over all directions	All dimensions and radii of curvature large compared with λ	4 7
Triangular corner reflector	$\frac{L^4}{3\lambda^2}(1 - 0.00076\theta^2)^2$	L = length of edge of reflector	At angle θ to axis of symmetry	Dimensions large compared with λ	5
Any elongated body of revolution	$\frac{16\pi^2 V^2}{\lambda^4}$	V = body volume	Along axis of revolution	All dimensions *small* compared to λ	8
Circular plate	$\left(\frac{4}{3\pi}\right)^2 k^4 a^6$	a = radius $k = 2\pi/\lambda$	Perpendicular to plate	$ka \ll 1$	8
Infinite plane strip	$\frac{1}{4\pi k}\left[\frac{\cos\theta \sin(2ka \sin\theta)}{\sin\theta}\right]^2$	$2a$ = width of strip θ = angle to normal	At angle θ	$ka \gg 1$	8
	$\frac{ka^2}{\pi}$		Perpendicular to strip	$ka \gg 1$ $\theta = 0$	

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8. Ruck, G. T., and others: "Radar Cross-Section Handbook," vols. I and II, Plenum Press, New York, 1970.

direction to source and receiver. This means, referring to Fig. 9.9, that the bistatic target strength with the source and receiver in the directions *OS* and *OR* from the target is the same as the monostatic target strength in the direction *OP* along the bisector of the angle *SOR*. This theorem, originating in physical optics, is said to be approximately true if the bistatic angle is considerably less than 180°. In the forward direction, where the bistatic angle equals 180°, physical optics also shows that the target strength of any large smooth object of projected area *A* equals 10 log A^2/λ^2, where λ is the acoustic wavelength, which must be small compared with all target dimensions. This is the same as the target strength of a flat plate of area *A* in the backward direction (Table 9.1).

Unfortunately, in the absence of measured data, it is not known how well these theoretical approximations apply, if they do at all, to the complex underwater targets of sonar.

9.7 Target-Strength Measurement Methods

The obvious and direct method of measuring the target strength of an underwater object is to place a hydrophone at a distance 1 yd from the object and to measure the ratio of the reflected (or scattered) intensity to the incident intensity. This method is impractical for a number of reasons. For many objects, it is difficult, if not impossible, to locate and place a hydrophone at this 1-yd point; even if it could be done, it would be difficult to separate the reflected sound from the incident sound at such a short distance. Moreover, the results would be invalid, in many cases, for use at longer ranges, since the target strength of objects like cylinders and submarines is different at short ranges than at long.

A more practical method is to use a reference target of known target strength, placed at the same range as the unknown, and to compare the levels of the echoes from the reference target and the target to be measured. The

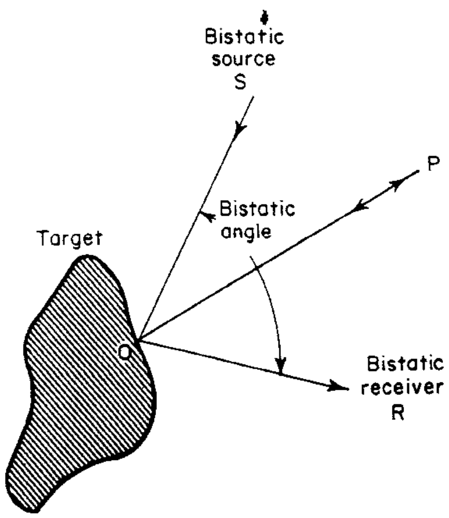

***fig. 9.9** The bistatic geometry. The direction OP is the bisector of the bistatic angle.*

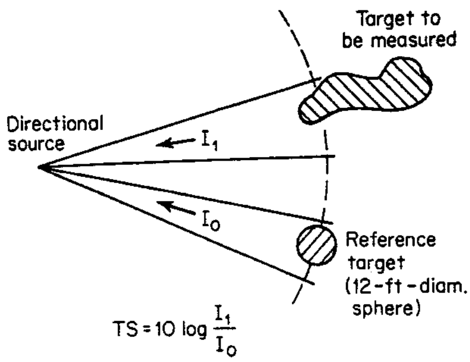

fig. 9.10 *Target-strength measurement using a reference sphere. A sphere of diameter 12 ft is placed at the same range as the target being measured. Using a directional active sonar, the intensities of the echoes are compared.*

method is illustrated in Fig. 9.10. If the reference target is a sphere of diameter 4 yd, its target strength is 0 dB. Then the target strength of the target to be measured will be 10 times the logarithm of the ratio of the echo intensity of the unknown target to that of the 0-dB reference target. Suitable corrections can easily be made for differences in range and size of the reference target. This straightforward comparison method is particularly suited to measurements on small objects at short ranges. For large objects, such as submarines at longer ranges, the handling and the size requirements of the reference sphere make the method impractical. In all cases, the construction and dimensions of the reference target must be carefully controlled to make sure that its target strength approximates that of the ideal shape. Because of its ease of handling and its higher effective target strength, a calibrated transponder is a substitute for such a passive reference target.

Most target-strength measurements have been made by what may be called the conventional method, in which measurements of the peak or average intensity of the irregular echo envelope are made at some long range and then reduced to what they would be at 1 yd. This reduction requires, in effect, a knowledge of the transmission loss appropriate to the time and place the echoes were measured, together with the source level of the sound source producing the echoes. The method is illustrated in Fig. 9.11. A number of echo-level measurements of a sonar target are made at some range r. The average level of the echoes is reduced to 1 yd by adding the known or estimated transmission loss; the difference between the reduced 1-yd level and the known source level is the target strength desired. The method employs the active-sonar equation written in the form

$$\mathrm{EL} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS}$$

where EL is the level of the echo. The equation is solved for the unknown, TS. This conventional method has the disadvantage of requiring an accurate knowledge of the transmission loss, which in turn requires either simple propagation conditions, or a special series of field measurements made for the purpose. Much of the scatter and diversity in existing target-strength data are doubtless attributable to erroneous transmission-loss assumptions and to

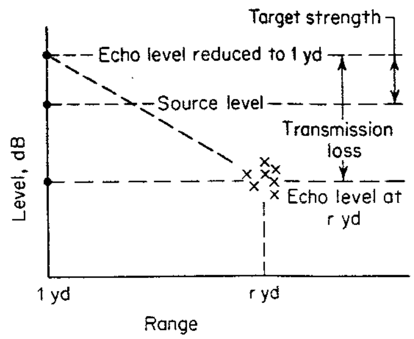

fig. 9.11 Target-strength measurement using echo levels reduced to 1 yd. The range, source level, and transmission loss must be known.

indiscriminate use of peak and average levels of the echo. Nevertheless, the method is basically simple and straightforward and requires no special equipment or instrumentation.

A method requiring no knowledge of the transmission loss, but needing special instrumentation, was used by Urick and Pieper (13). A measurement hydrophone and a transponder located about 1 yd from it were installed on the target submarine. On the measuring vessel (a surface ship) a hydrophone was suspended near the sound source producing the echoes to be measured. The relative levels of echo and transponder pulses were recorded aboard the surface ship; the relative levels of the incoming pulse and the transponder pulse were recorded aboard the submarine. As will be evident from Fig. 9.12, the target strength of the submarine is simply the difference in level between the two level differences recorded on the two vessels. The transponder serves, in effect, to "calibrate out" the underwater transmission path between the two vessels. No absolute calibration of the transducers used is needed, and the range separating the vessels need not be known.

9.8 Target Strength of Submarines

The target strength of submarines, of all underwater targets, has had the earliest historical attention and has been relatively well known from work

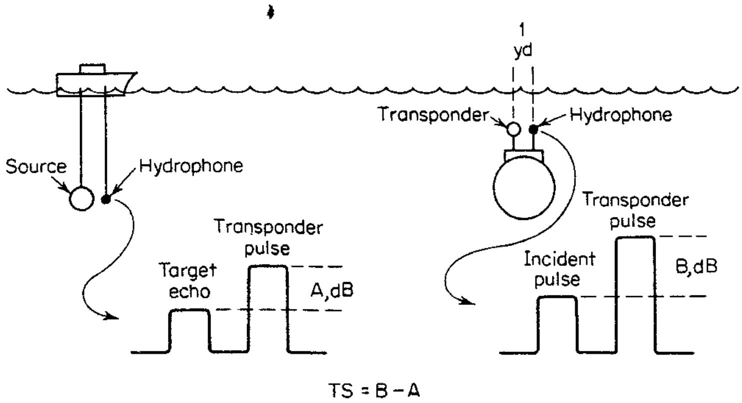

fig. 9.12 A transponder method of target-strength measurement. No calibrations or knowledge of transmission loss are necessary.

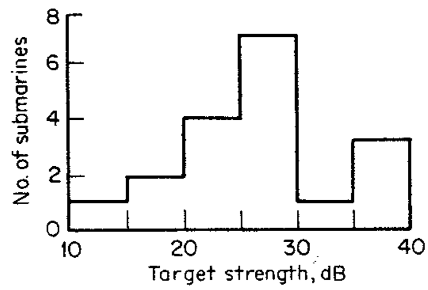

fig. 9.13 *Histogram showing the spread of the reported target strenths of 18 submarines at beam aspect, taken from the literature.*

done during World War II. This work has been well summarized in the NDRC Summary Technical Reports (14, 15). The present treatment of the subject will center about the variations of target strength with aspect, frequency, ping duration, depth, and range. The submarines considered will be limited to fleet-type diesel-powered submarines.

It should be emphasized at the outset that submarine target strengths are perhaps most noteworthy for their variability. Not only do individual echoes vary greatly from echo to echo on a single submarine, but also average values from submarine to submarine, as measured by different workers at different times and reduced to target strength, are vastly different.

Figure 9.13 shows the distribution of target strengths at beam aspect of diesel-powered submarines as reported in 18 separate reports by different observers using different sonars. As a result, the following discussion of the subject will be concerned with trends and broad effects, with the exception that individual measurements will show great differences from the mean or average values.

Variation with aspect Figure 9.14 shows two examples of the variation of target strength with aspect around a submarine. Example A is a typical World War II determination (16) at 24 kHz with each point representing an average of about forty individual echoes in a 15° sector of aspect angle. Example B is the result of a postwar measurement (13) in which about five echoes were averaged in each 5° sector. Plots of this kind are based on measurements at sea of echoes from a submarine which runs in a tight circle at a distance from the source-receiver ship. Alternatively, the latter may circle a submarine running on a straight course at a slow speed.

The two examples of Fig. 9.14 illustrate the variability of target-strength measurements mentioned above. There is first a point-to-point variability with aspect that is due to the variability in level of individual echoes. There is also an average difference of about 10 dB between the two sets of measurements, with A being more typical of other determinations.

Nevertheless, when viewed in a broad fashion, the aspect dependence of target strength may be considered to have the pattern shown in Fig. 9.15. This "butterfly" pattern has the following characteristics:

1. "Wings" at beam aspect, extending up to about 25 dB and caused by specular reflection from the hull.
2. Dips at bow and stern aspects caused by shadowing of the hull and wake.
3. Lobes at about 20° from bow and stern, extending 1 or 2 dB above the general level of the pattern, perhaps caused by internal reflections in the tank structure of the submarine. These lobes do not appear in the aspect plots of nuclear-powered submarines not having ballast and fuel tanks outside the pressure hull.
4. A circular shape at other aspects due to a multiplicity of scattered returns from the complex structure of the submarine and its appendages.

All the characteristics of this idealized pattern are seldom seen in individual measurements. They may be absent entirely or lost in the scatter of the data. For example, Fig. 9.16 illustrates aspect plots of two submarines measured more recently at a frequency near 20 kHz with a pulse length of 80 ms while the submarines circled at a range of roughly 1,500 yd. Each plotted point

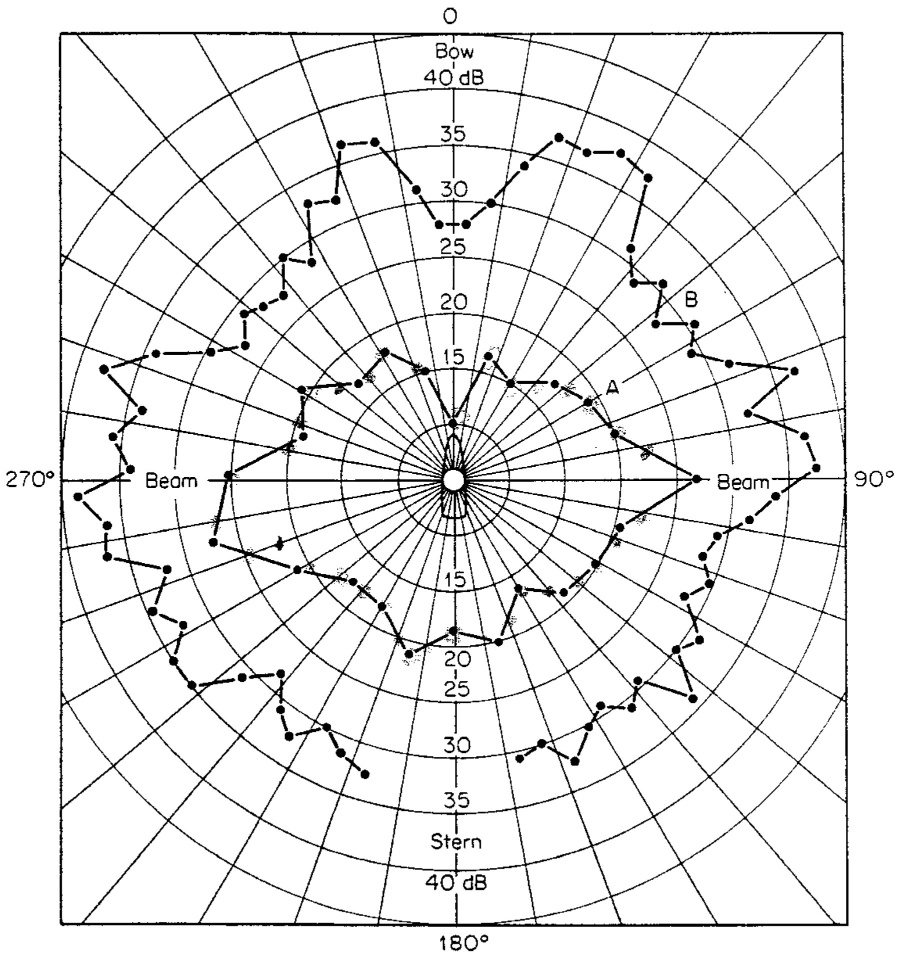

fig. 9.14 Two determinations of the target strength of a submarine at various aspects. Example A (Ref. 15) is more typical of other determinations than B (Ref. 13).

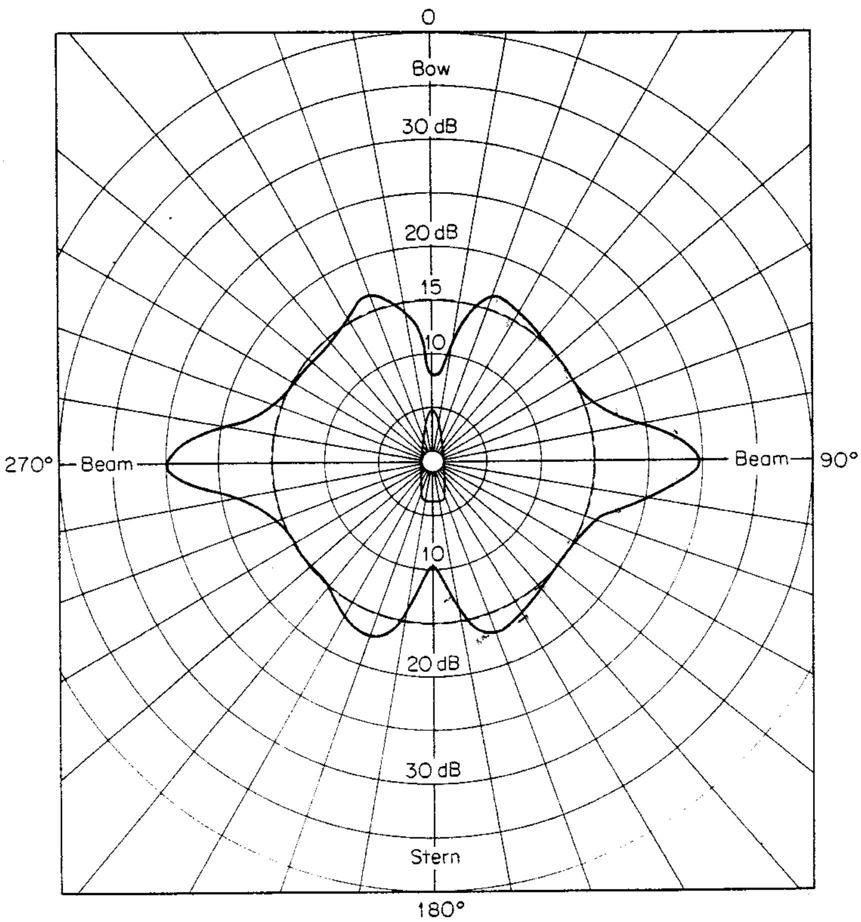

fig. 9.15 *The "butterfly" pattern of the aspect variation of submarine target strength.*

represents a single echo. Particularly striking is the variability between echoes during the circling maneuver, as well as the difference of about 5 dB between the target strengths of the two submarines when averaged over all aspects. One is hard-pressed to see in these data any sign of the "butterfly" pattern just described. Aspect patterns showing wide echo-to-echo variability are well known in radar (17). The tremendous variability between echoes is caused by a changing phase relationship between the different scatterers and reflectors on the target; as the target aspect changes, the various contributions add up with different phase relationships so as to produce a variable echo amplitude. Echo fluctuations are observed even from a target at an apparently constant aspect, as a result of the small changes of heading that must be made by the helmsman, or by the pilot of an aircraft, attempting to steer a steady course.

Variation with frequency Target-strength data were obtained during World War II (18) at 12, 24, and 60 kHz in an attempt to determine the effect of frequency on target strength. This attempt was unsuccessful, and it was concluded at that time that, if any frequency dependence existed, it was lost in the

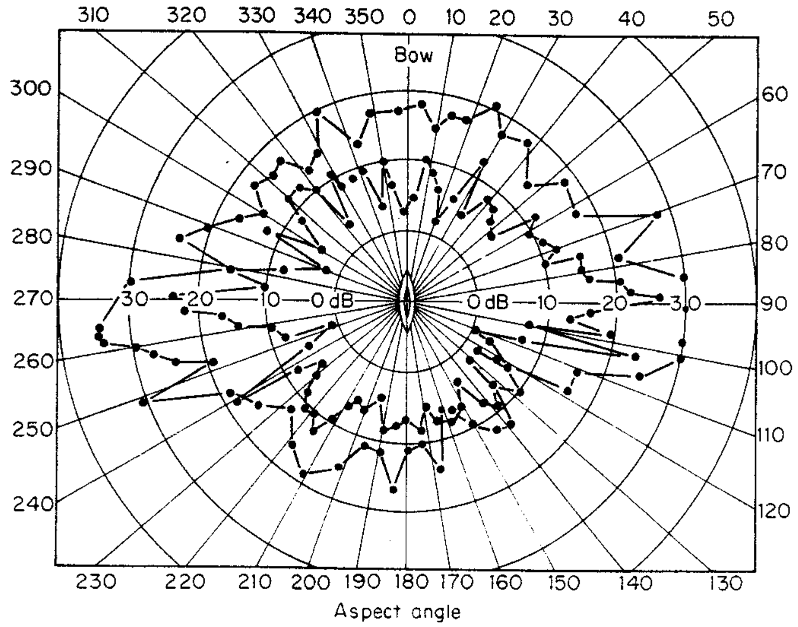

fig. 9.16 Measurements of target strength versus aspect for two submarines. Each dot represents a single echo as the target circled at a distance.

uncertainties of the data. The cause of this apparent frequency independence must be the many processes and sources that govern the return of sound from a submarine.

Variation with depth Except for the contribution of sound returned from the submarine's wake, no effect of depth on target strength has been established or expected. Depth effects on the echo are more likely the result of changing sound propagation with changing depth in the sea, instead of a depth effect on the submarine itself.

Variation with range For two reasons, the target strength of submarines is likely to be less at short ranges than at long ranges. One is the failure of a directional sonar, if one is used for the target-strength measurement, to insonify the entire target. The other is the fact that the echo of some geometrical forms does not fall off with range like the level from a point source. The solid curve in Fig. 9.17 shows the variation of echo intensity with range for a cylinder of length L at "beam" aspect. The intensity falls off like $1/r$ at short ranges ("cylindrical spreading") and like $1/r^2$ at long ranges ("spherical spreading") with a transition range approximately equal to L^2/λ. An echo at a short range r_1, when reduced to 1 yd by applying the transmission loss appropriate for a point source, would yield an apparent target strength TS_1 that would be less than the value TS_2 obtained with a long-range echo. Also, the target strength of an infinitely long cylinder, for which all points at a finite distance are in the near field or Fresnel region of the cylinder, is seen in Table 9.1 to increase linearly with range. The former effect—that of failure to insonify all the target—would apply to conditions of aspect and frequency where scattering by numerous scatterers on or in the target is the dominant echo-producing process; the latter effect applies to specular reflection. Both effects cause the short-range target strength of submarines to be less than the long-range target strength.

Variation with pulse length The target strength of an extended target, such as a submarine, may be expected to fall off with decreasing pulse length, inasmuch as a short pulse must fail to insonify the entire target. Thus, Fig. 9.18 illustrates that the target strength of an extended target should increase with the pulse length (in logarithmic units) until the pulse length is just long enough for all points on the target to contribute to the echo simultaneously at some instant of time. This occurs when the ping duration τ_0 is such that

$$\tau_0 = \frac{2l}{c}$$

where l = extension in range of target
c = velocity of sound

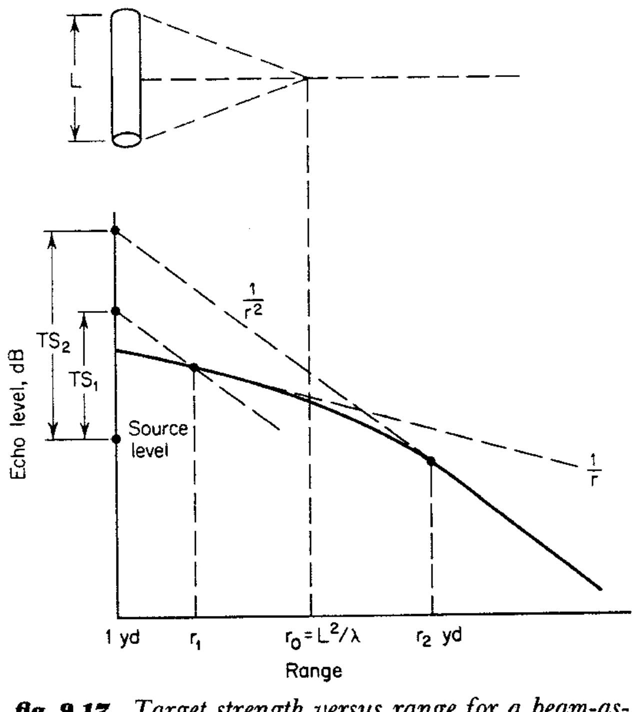

fig. 9.17 *Target strength versus range for a beam-aspect cylinder. At ranges less than r_0, the echo level varies with range like $1/r$ rather than $1/r^2$. This causes a lower target strength at short ranges than at long ranges ($TS_1 < TS_2$) if a $1/r^2$ transmission loss is used for the reduction to 1 yd.*

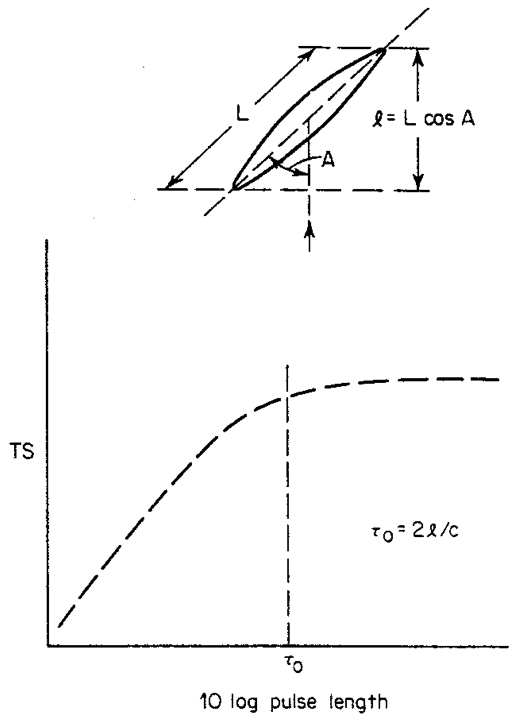

fig. 9.18 *Variation with pulse length. The target strength increases until the pulse length is great enough for the entire target to contribute to the echo at some one instant of time. This occurs at pulse length $\tau_0 = 2l/c$.*

If the target is of length L, then at aspect angle A,

$$l = L \cos A$$

This theoretical effect of reduced ping duration is not noticeable in target-strength measurements at beam aspect, where the extension in range is small and where specular reflection is the principal echo formation process, nor in measurements of peak target strength where individual target highlights are being measured.

9.9. Target Strength of Surface Ships

Because surface ships are not important targets for active sonars, comparatively little data are available on their target strengths. Three series of measurements at frequencies from 20 to 30 kHz were made during World War II on a total of 17 naval and merchant ships (19). They yielded beam-aspect values of 37, 21, and 16 dB for the three different groups of measurements and values of 13, 17, and 14 dB for corresponding off-beam target strengths. Standard deviations between 5 and 16 dB are quoted for these values. The small amount of available data show similar effects of aspect and range, as for submarines.

9.10 Target Strength of Mines

Modern mines are quasi-cylindrical objects a few feet long and 1 to 2 ft in diameter, flat or rounded on one end, and containing protuberances, depressions, and fins superposed on their generally cylindrical shape. Such targets should be expected to have a high target strength at "beam" aspect, as well as at aspects where some flat portion of the shape is normal to the direction of incidence; at other aspects, a relatively low target strength should be had. Measured target strengths range from about +10 dB within a few degrees of beam aspect, to much smaller values at intermediate aspects, with occasional lobes in the pattern attributable to reflections from flat facets of the mine shape. By Table 9.1, the target strength of a cylinder of length L, radius a, at wavelength λ is at long ranges

$$\text{TS} = 10 \log \frac{aL^2}{2\lambda}$$

If a be taken as 0.2 yd, L = 1.5 yd, and λ = 0.03 yd, corresponding to a frequency of 56 kHz, then

$$\text{TS} = 10 \log \frac{0.2 \times (1.5)^2}{2 \times 0.03} = 9 \text{ dB}$$

in approximate agreement with measurements on mines at beam aspect. The principal effects of frequency, aspect, range, and pulse length described for submarines apply for mines generally as well.

9.11 *Target Strength of Torpedoes*

A torpedo is, like most mines, basically cylindrical in shape with a flat or rounded nose. When specular reflection can be presumed to be the principal echo formation process, the target strength of a torpedo can be approximated by the theoretical formulas. An approaching torpedo of diameter 20 in. (radius = 0.28 yd) and having a hemispherical nose with a diameter equal to that of the torpedo, would have a target strength equal to $10 \log [(0.28)^2/4] = -17$ dB. At beam aspect its target strength could be approximated by the cylindrical formula illustrated for mines.

9.12 *Target Strength of Fish*

Fish are the targets of fish-finding sonars. Their target strengths are of interest for the optimum design of such sonars and, ideally, might be used for acoustic fish classification—that is, for estimating the number, type, and size of fish when fish finders are employed at sea.

Extensive data on the target strengths of fish of different species have been reported by Love (20, 21), both for fish in dorsal aspect (looking down at the fish) and in side aspect (looking broadside). Echoes from live fish, anesthetized to keep them motionless, were measured in a test tank, and the measurements were reduced to target strength in the conventional way (Sec. 9.7). Eight frequencies over the range 12 to 200 kHz were used; the fish specimens ranged in length between 1.9 and 8.8 inches. The results showed a strong dependence on the size of the fish, as measured by its length, and only a weak dependence on frequency or wavelength. When combined with older data reported by others, it was found that the measurements at dorsal aspect could be fitted by the empirical equation

$$TS = 19.1 \log_{10} L - 0.9 \log_{10} f - 54.3$$

where L is the fish length in inches, and f is the frequency of kilohertz. With L in centimeters, this equation becomes

$$TS = 19.1 \log_{10} L - 0.9 \log_{10} f - 62.0$$

The range of validity was $0.7 < L/\lambda < 90$; over this range an individual fish had a target strength differing on the average by about 5 dB from that given by the equation. Figure 9.19 shows TS plotted against L for frequencies 10 and 100 kHz according to these expressions. At side aspect, the measured values were on the average 1 dB higher at $L/\lambda = 1$ and 8 dB higher at $L/\lambda = 100$ than those at dorsal aspect. Additional measurements at lower frequencies over the range 4 to 20 kHz have been reported by McCartney and Stubbs (22), with generally similar results. These investigators point out that, at least in their frequency range, the swim bladder of the fish is the major cause of the backscattered return. Fish without swim bladders, such as mackerel, have a target strength some 10 dB lower than those that do, such as cod (23).

Although it is biologically incorrect to speak of whales as "fish," we may note

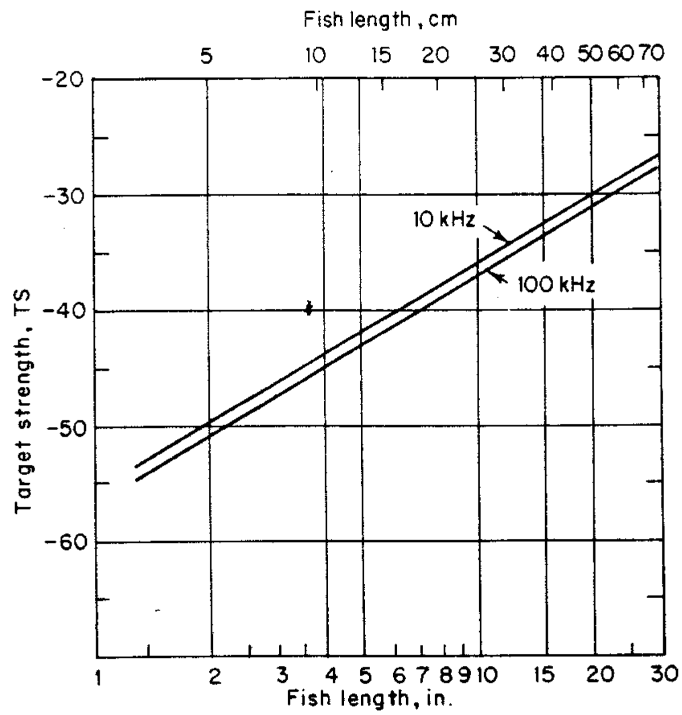

fig. 9.19 Target strength of fish as a function of fish length for two frequencies, according to expressions given in text.

here, if only as a curiosity, that the target strength of one species of whale in the open sea has been reported (24). Echoes were obtained from a number of humpback whales as they cavorted around the Argus Island oceanographic tower off Bermuda. At 20 kHz, two whales about 15 yd long were found to have a target strength of +7 at side aspect and −4 dB at head aspect; at 10 kHz, one smaller whale 10 yd long had a target strength of +2 dB at side aspect. These values are roughly what would be obtained by extrapolations in Fig. 9.19. Strange to say, they are not greatly different from what would be obtained from the expression TS = 10 log $R_1R_2/4$ for the target strength of a large curved object of the same dimensions (Sec. 9.2).

9.13 Target Strength of Small Organisms

The target strength of various forms of zooplankton, such as squid, crabs, euphausid shrimp, and copepods has been reported by a number of investigators. The results have been reviewed by Penrose and Kaye (25) who found, strangely enough, that the expression of Love given above fitted the measurements fairly well. Thus copepods 3 mm long were found to have a target strength of about −80 dB, crabs 30 mm in size, −60 dB; squid 100 mm in size, −45 dB. Little or no frequency dependence was found, although Greenlaw (26), using preserved specimens in the frequency range 200 to 1,000 kHz, observed a strong (20 log f) increase with frequency. The spread of measured data is large and the mechanism by which a small marine organism—which may or may not have a hard shell or contain a bubble of gas—interacts with sound is still not clear.

9.14 Echo Formation Processes

Complex underwater targets return sound back to the source by a number of processes. These processes will all occur, in general, for a complex target like a submarine, but only one or two will be dominant under any particular conditions of frequency and aspect angle.

Specular reflection The most simple and best understood echo formation process is *specular reflection*. It is illustrated by the return of sound from large spheres or convex surfaces, as described earlier in this chapter. In this process, the target remains stationary and does not move in the sound field and thereby generates a reflected wave having a *particle velocity* just sufficient, in wave theory, to cancel that of the incident wave over the surface of the object. Alternatively, the reflecting surface may be *soft* instead of *hard* or stationary, so as to form a reflection in which the *pressures* of the two waves will cancel. A specular reflection has a waveform that is a duplicate of the incident waveform and can be perfectly correlated with it. For submarines and mines, specular reflection appears to be the dominant process at beam aspects, where a much-enhanced return is observed and where a short incident pulse has a faithful replica as an echo.

Scattering by surface irregularities Irregularities, such as protuberances, corners, and edges, that have small radii of curvature compared with a wavelength, return sound by scattering rather than reflection. Most real objects possess many such irregularities on their surface, and the scattered return is composed of contributions from a large number of such scattering centers. When only a few scatterers on the underwater target are dominant, they form *highlights,* which may be observable in the echo envelope. Submarines, especially the older types, possess numerous scattering irregularities on the hull, such as the bow and stern planes, railings, periscopes; of these protuberances, the conning tower is likely to be a strong reflector or scatterer of sound.

Penetration of sound into the target Underwater targets seldom remain rigid under the impact of an incident sound wave, but move or deform in a complex manner. This reaction may be thought of as penetration of sound into the target and a complex deformation of the target by the exciting sound wave.

In solid metal spheres in water, Hampton and McKinney (27) found considerable experimental evidence that acoustic energy in the frequency range 50 to 150 kHz penetrated into solid spheres a few inches in diameter and thereby produced a complex echo envelope and a target strength which varied by as much as 30 dB with frequency. A theoretical study by Hickling (28) of hollow metal spheres in water demonstrated that part of the echo originates from a kind of flexural wave moving around the shell. Such surface waves were also observed experimentally by Barnard and McKinney (29) in a study of solid and air-filled cylinders in water. We have already described these kinds of deformation waves in Sec. 9.4.

Submarines are structurally much more complicated than the simple forms just mentioned. Figure 9.20 shows cross-sectional views of a fleet-type submarine of basically World War II construction. The hull is essentially a quasi-cylindrical pressure hull surrounded by a tank structure of thin steel. Penetration of sound into the tank structure is relatively easy, and a return of sound by corner reflectors should be expected. These internal reflections may be the cause of the enhanced target strength at about 20° off bow and stern in the butterfly pattern of Fig. 9.15. In addition, scattering and resonance effects in the tank structure are likely to be sources of the echo at off-beam aspects. Finally, the pressure hull itself may be expected to contribute a scattered return at some aspect angles.

Whenever a regular repeated structure or appendage exists on a target, an enhanced echo is likely to occur at the frequency and angle for which the scattered returns reinforce one another in a coherent manner. This is a diffraction-grating effect; it will occur when the projected distance between structural components is a half-wavelength or a multiple thereof. A regularly structured target appears to act like an array of radiating elements, and produces the same beam pattern in its echo as would a line of equally spaced elements at twice the spacing. This is an alternative explanation of the 20°

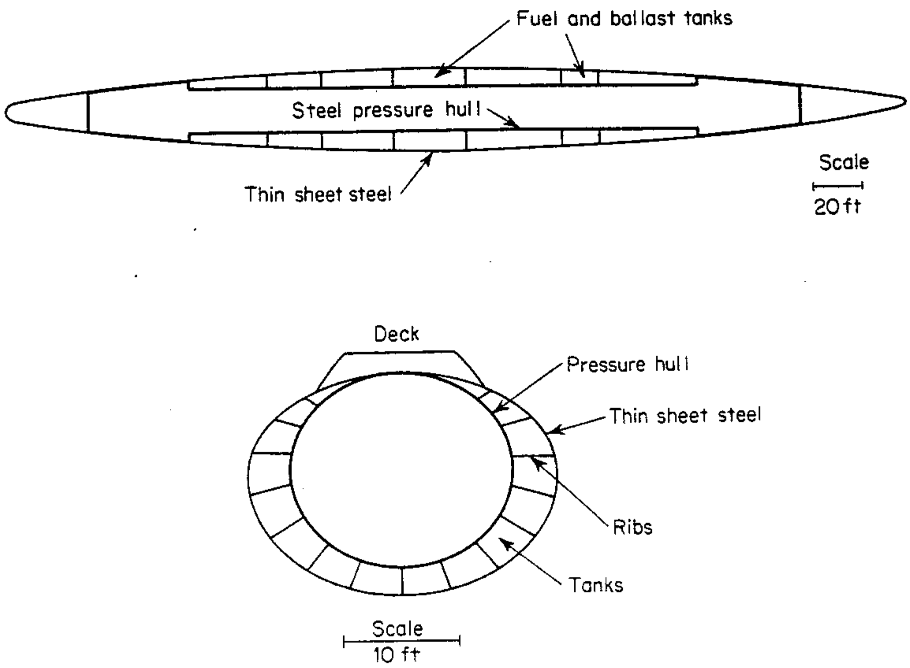

fig. 9.20 *Diagrammatic fore-and-aft and athwartship cross sections of a World War II U.S. fleet submarine.*

"ears" of the butterfly pattern just mentioned; the tank structure, the framing of the hull, or some other regularly repeated structural component may provide the regularity needed for selective reinforcement of the echo.

Resonant effects Certain incident frequencies may correspond to various resonance frequencies of the underwater target. Such frequencies will excite different modes of oscillation or vibration of the target and give rise, in principle, to an enhanced target strength. Figure 9.21 is a pictorial description of a number of possible oscillatory modes of a compressible, flexible cigar-shaped object. When the sonar frequency is low enough, such modes may be excited by the incident sound wave and contribute to the target strength to an extent depending on the aspect and the Q or damping constant of the oscillatory mode. However, it should be pointed out that those modes which are good radiators of sound have a high damping constant because of radiation loading by the surrounding fluid, and as a result they would not necessarily give rise to a much greater target strength. Similarly, slightly damped modes of high Q might be poor reradiators of sound and thereby be poor contributors to the target strength. Such slightly damped modes would require a long sonar pulse of closely matched frequency for their excitation. It is even possible that resonant vibratory modes may be accompanied by a *lower* target strength if high internal losses in the target cause absorption of the incident energy, or if the mode is such that sound is reradiated, at resonance, into directions other than into the specular direction.

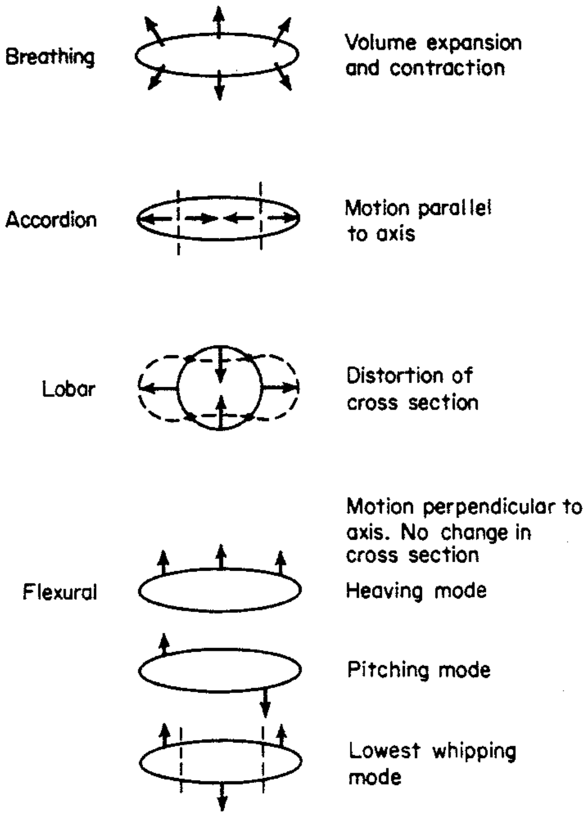

fig. 9.21 *Various possible resonant vibratory modes of a cigar-shaped body.*

A resonance of an entirely different type is the flexural resonance of the plates of which an underwater target like a submarine is composed. At certain angles a steel plate has been shown by the work of Finney (30) to be transparent to sound because of coupling between shear waves in the plate and sound waves in the surrounding water.

9.15 Reduction of Target Strength

It is sometimes desired to do something to a target, other than make major structural and compositional changes to it, for the purpose of reducing its target strength. This kind of acoustic camouflage can be achieved in a variety of ways. These are listed in Table 9.2.

table 9.2 Methods of Target Strength Reduction

Wavelength Large:* Low frequencies
Volume reduction
Wavelength Small:* High frequencies
Body shaping
Anechoic coatings
Viscous absorbers
Gradual-transition coatings
Cancellation coatings
Quarter-wave layer
Active cancellation

* Compared to all dimensions of the body.

At low frequencies, where the wavelength is large compared to all dimensions of the object, the only recourse is to reduce the *volume* of the target. This follows because, as we have seen, the target strength of a small sphere (Sec. 9.3) or of any small smooth object (Table 9.1) depends only on its volume at a fixed frequency. It follows that no alteration of body shape or application of a coating will be effective on a body that is small compared to a wavelength.

However, at high frequencies and short wavelengths, a variety of techniques are applicable, at least in principle. One is to *change the shape* of the body, if it is possible to do so, in such a way as to make the two principal radii of curvature (R_1R_2, Sec. 9.2) everywhere small, avoiding in particular the infinities characteristic of flat plates and cylinders. The body shape should be smooth, without protuberances, holes, and cavities that act as scatterers of sound. In radar, a shape that has received much attention for missile applications is a cone with hemispherical base; this presents a particularly low target strength when viewed in the direction toward the conical tip. In radar, the radar cross section of the body need be minimized only in one (the forward) direction, whereas in sonar, a reduction usually must be achieved in many or all directions. For this reason, other shapes will be useful for sonar applications.

Anechoic coatings are materials that are cemented or attached to the body in order to reduce its acoustic return. The most important of these are various *viscous absorbing coatings* which attenuate the sound reaching, and returning from, the target by the process of viscous conversion to heat. Metal-loaded rubbers are an example of this kind of coating (31); here the tiny air cavities accompanying the metal particles cause a shear deformation of the rubber and a loss of sound to heat. Much larger air cavities causing shear deformation in rubber were employed in the Alberich coating used by the German Navy in World War II (32). This coating comprised a sheet of rubber 4 mm thick containing cylindrical holes 2 and 5 mm in diameter, with an overlying thin sheet of solid rubber to keep water out of the holes. This particular coating was effective in the octave 9 to 18 kHz; a number of German submarines were coated with it during the latter part of the war. A *gradual transition coating* consists of wedges or cones of lossy material with their apex pointing toward the incident sound. An example of this is a mixture of sawdust material called "insulkrete," described by Darner (33) for lining a tank to make it anechoic. This particular type of coating is massive and relatively fragile in construction for use on sonar targets.

A *cancellation coating* consists of alternate layers of acoustically hard and soft materials that reflect sound with opposite phase angles, so that no sound is returned from the target. Unfortunately, the cancellation occurs only at normal incidence, and there is little or no effect in other directions. A *quarter-wave layer* is a coating $\lambda/4$ in thickness having an acoustic impedance (ρc) equal to the geometric mean between the materials on either side, as, for example water and steel (34). Theory shows that under these conditions the layer is a perfect impedance match between the two materials, and no sound is reflected. But, because it is effective only at a single frequency (plus odd multiples thereof) and then only at normal incidence, the quarter-wave coating is of no value for practical sonar applications. Finally, we can mention the principle of *active cancellation*, wherein the incoming sound is monitored on the target and an identical signal is generated 180° out of phase to it by a small sound source. This technique has been used for reducing reflections in a tube for transducer calibrations (35), but requires expensive instrumentation; in any case, it would have little value for reducing reflections from the large complex targets of sonar.

9.16 Echo Characteristics

Echoes from most underwater objects differ from the incident pulse in a number of ways other than intensity, as described by the parameter target strength. The reflecting object imparts its own characteristics to the echo; it interacts with the incident sound wave to produce an echo that is, in general, different in wave shape and other characteristics from the incident pulse. These differences are useful to the sonar engineer in two ways: they may be employed as an aid in *detection,* as in filtering with narrow-band filters to enhance an echo buried in reverberation; they may be utilized to assist in target *classification* to distinguish one type of target from another, as in distinguishing a submarine from a school of fish.

Some distinguishing characteristics of echoes are:

Doppler shift Echoes from a moving target are shifted in frequency by the familiar doppler effect (36) by an amount equal to

$$\Delta f = \frac{2v}{c} f$$

where v = relative velocity or range rate between source and target
c = velocity of sound (in same units as v)
f = operating frequency of transmitter

In practical terms, and for a sound velocity of 4,900 ft/s,

$$\boxed{\Delta f = \pm 0.69 \text{ Hz/(knot)(kHz)}}$$

where the range rate is in units of knots and the sonar frequency is in kilohertz. An echo from an approaching target with a 10-knot relative velocity and a frequency of 10 kHz would thus be shifted higher in frequency by 69 Hz. The ± sign indicates that an approaching target produces an echo of higher frequency ("up-doppler"), and a receding target one of lower frequency ("down-doppler").

Extended duration Echoes are lengthened by the extension in range of the target. Whenever an underwater target is such that sound is returned by scatterers and reflectors distributed all along the target, the entire area or volume of the target contributes to the echo. For a target of length L at an aspect angle θ, the incident pulse is lengthened in duration by the time interval

$$\frac{2L\cos\theta}{c}$$

for the monostatic case, and by

$$\frac{L}{c}(\cos\theta_i + \cos\theta_r)$$

for the bistatic case with incidence at aspect angle θ_i, and an echo return at angle θ_r. This time elongation of the echo is most noticeable when short sonar pulses are employed. It occurs only for complex targets composed of numerous distributed scatterers and is negligible when specular reflection is the most important process of echo formation. Most sonar echoes are elongated, however, and so provide a clue concerning the size, and therefore the nature, of the echoing object.

Some actual measured data on the duration of echoes from a submarine target as a function of aspect angle are shown in Fig. 9.22. In this plot, each

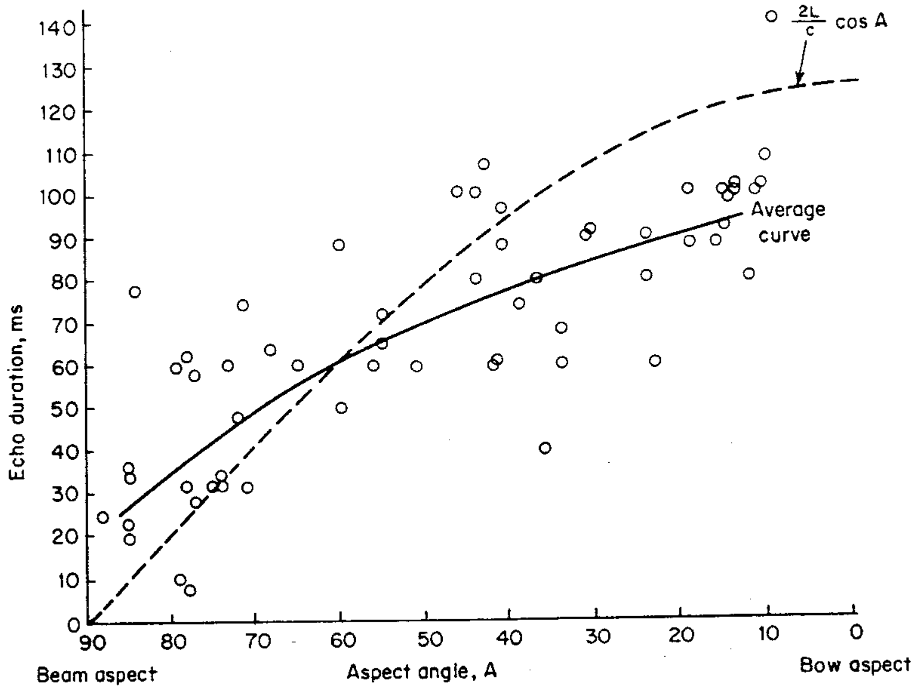

fig. 9.22 Echo duration at different aspect angles of a submarine target. Each point represents a single echo from an explosive source.

point represents the time duration of an explosive echo at the particular aspect angle at which it occurred. We observe that the theoretical relationship $t = 2(L/c) \cos A$ is only a rough approximation to the observations summarized by the average curve. The echoes are longer than they should be near beam aspect, probably because of multipath transmission (more particularly, the surface reflected path) from source to target and back again; the echoes are shorter than they should be near bow aspect, probably because of shadowing of the stern portions of the hull by the bow.

Irregular envelope The echo envelope is irregular, especially where specular reflection is not important. This irregularity arises from acoustic interference between the scatterers of the target. For some targets, individual highlights in the echo may be identified as arising from individual strong echoing portions of the target; for example, the conning tower of a submarine may yield a recognizable strong return of its own as part of the echo. Most often, however, the sonar echo from a sinusoidal ping is an irregular blob, without distinguishing features, that varies in envelope shape from echo to echo as the changing phase relationships among the scatterers and the propagation paths to and from the target take effect. Figure 9.23 is a sequence of three echoes from a short-range oblique-aspect submarine taken at intervals one second apart using a sonar with a pinglength of 15 ms. From this sequence we should note the rapid variability of the complex structure of the echo envelope and its extended duration relative to the 15-ms outgoing pulse.

table 9.3 Nominal Values of Target Strength

Target	Aspect	TS, dB
Submarines	Beam	+25
	Bow-stern	+10
	Intermediate	+15
Surface ships	Beam	+25 (highly uncertain)
	Off-beam	+15 (highly uncertain)
Mines	Beam	+10
	Off-beam	+10 to −25
Torpedoes	Bow	−20
Fish of length L, in.	Dorsal view	$19 \log L - 54$ (approx.)
Unsuited swimmers	Any	−15
Seamounts	Any	+30 to +60

Modulation effects At stern aspects on propeller-driven targets, the propeller may amplitude-modulate the echo in the same way that the propeller of an aircraft is known (37) to modulate a radar echo. The propeller thus produces a cyclic variation in the scattering cross section of the target. Another possible form of modulation can arise from interaction between the echo from a moving vessel and the echo from its wake. The difference in frequency between the two may appear as beats, or amplitude variations, in the envelope of the combined echo from the hull and wake at certain aspect angles.

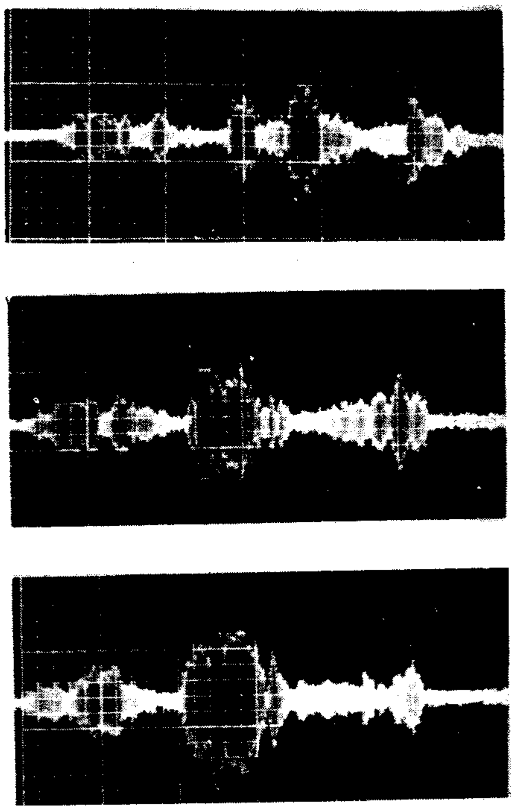

fig. 9.23 *Photographs of three submarine echoes taken one second apart. The width of the horizontal scale is 120 ms; the sonar pinglength was 15 ms.*

9.17 Summary of Numerical Values

Table 9.3 is a summary of target-strength values for the underwater targets described in this chapter, plus two others. As previously mentioned, these are subject to considerable variation in individual measurements on targets of the same type, and the target-strength values given are to be regarded only as nominal values useful for first-cut problem solving.

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