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Review of target strength information for waterside security applications

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REVIEW OF TARGET STRENGTH OF CYLINDRICAL OBJECTS FOR WATERSIDE SECURITY APPLICATIONS

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Abstract: *Estimates of the target strength of objects, such as for example scuba tanks and swimmer delivery vehicles, are parameters of interest in all phases of the design of waterside security systems. Results of numerical target strength computations are presented for a variety of simple cylindrical objects, which can be used as fac-simile targets in the design of harbor protection sonars. The discussion covers the structural resonance-dominated and material dependant low-frequency regime, where the acoustic wavelength is of the same order as a characteristic size of the target, as well as the high frequency regime, which is of interest to imaging-sonar applications. Monostatic and bistatic scattering geometries are considered. The numerical results obtained with a validated numerical model are compared to simple engineering approximations for perfectly rigid spheres and finite cylinders. This makes it possible to verify the numerical model results and to establish the regions of validity of the simple engineering approximations for practical applications.*

Keywords: *Target Strength, Diver Detection, Resonant Scattering*

1. INTRODUCTION

The target strength (TS) is one of the ingredients of the sonar equation for active acoustic detection applications [1]. At the present time, a number of port and asset/force protection sonar systems have been developed, and various novel techniques for the detection of intruders and underwater threats are being investigated, covering the low-frequency band (resonance dominated frequencies, at which the acoustic wavelength is of the same order as the target size) and high frequencies, up into the imaging sonar regime. At all stages of the development of such systems, information about the TS is essential in guiding the engineer's decisions regarding the optimal frequency band for a given application and the optimal target-receiver configurations.

The purpose of this paper is to provide TS values over a broad frequency range for targets representative of a scuba tank, immersed in an infinite volume of water, and for air cavities, which to a first level of approximation can be used to represent the air-filled cavities of a human diver (such as lungs and bowels), provided that the geometry is rescaled to the appropriate equivalent volume. In all cases, the results are obtained from a frequency-domain finite element (FE) model, with Helmholtz-Kirchhoff integral post-processing for computing the far field [2, 3]. The problem geometry and physics are 3-D, and no 2-D assumptions are made. Comparisons with asymptotic formulae for simplified shapes [1, 4] are also provided, and indications are given regarding the frequency regimes at which the asymptotic formulae can be applied to obtain practical TS estimates for the elastic targets.

Section 2 contains the TS results for the scuba tank, considering first a perfectly rigid cylinder (zero displacement boundary conditions) and then a perfectly soft cylinder (pressure release boundary conditions mimicking an air cavity). Finally we consider a more realistic steel tank filled with air at sea-level pressure (*i.e.* the inclusion is a cavity with pressure release conditions on the inner surface of the target). The scuba tank is modelled as a finite cylinder of length L=60 cm with hemispherical end-caps and an outer radius of a=10 cm. The frequencies of the incident plane waves are varied from 100 Hz to 100 kHz, at increments of 25 Hz, and monostatic (backscattering) as well as bistatic (forward scattering) results are presented for broadside and end-on incidence.

Throughout this paper, the target strength [1] is defined as TS = $20 \log_{10}(R\,|p^{scat}|/|p^{inc}|)$, where R is the distance between the nominal target center and the receiver (assumed here to be at 100 m, a distance at which the TS is converged to a quantity independent of R), $|p^{scat}|$ is the amplitude of the scattered pressure field and $|p^{inc}|$ is the incident plane wave amplitude. In all the examples presented, the TS is plotted as a function of the acoustic frequency f, as well as of the dimensionless frequency $ka=2\pi\,a/\lambda$, where λ is the acoustic wavelength. This makes it possible to obtain the TS information for other targets of the same aspect ratio (and same ratio between a and the shell thickness in the elastic case), by identifying the TS values at the appropriate ka. The properties of the water are ρ=1000 kg/m^3 and c=1500 m/s.

2. SCATTERING FROM A CYLINDRICAL SHELL OF VARIABLE THICKNESS: A SIMPLE MODEL OF A SCUBA TANK

The TS for an axisymmetric body representative of a scuba tank (Fig. 1), is computed for three different cases: (i) perfectly rigid body (zero normal displacement boundary

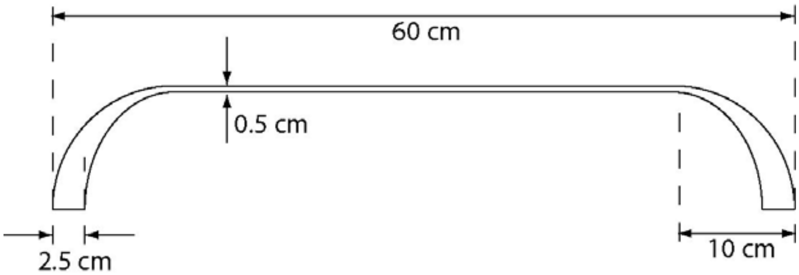

Fig. 1: Drawing of half a cross-section of the scuba tank model. The tank is surrounded by an ideally infinite volume of water.

conditions on the wet surface of the object), (ii) perfectly soft body (zero pressure boundary conditions on the wet surface) and (iii) steel shell, which is expected to feature elastic resonances, particularly in the backscattering direction. Case (ii) is representative of an air-filled cavity (at sea-level pressure), such as for example the lungs and bowels of divers, with the typical low-frequency bubble resonance effects neglected. A rescaling of the frequency and target size is necessary to obtain values which are effectively representative of the TS of lungs and/or bowels. This can be achieved by selecting the appropriate *ka* value in the TS plot.

2.1. Perfectly Rigid Cylinder

The target of Fig. 1 is assumed to be perfectly rigid, *i.e.* zero total normal displacement boundary conditions are applied at the interface between the cylinder and the surrounding water. The back- and forward scattering TS for a broadside incident plane wave are presented in Fig. 2, together with the asymptotic estimate for a perfectly rigid flat end-capped cylinder. The asymptotic approximation is obtained from the expression $TS_{Urick}=10\ \log_{10}(ka\ L^2/(4\pi))$, which is valid at high frequencies and at large receiver distances [1]. TS_{Urick} is computed for two cases: a flat end-cap cylinder of the same length L as the scuba tank model (labelled "Urick asymptotic 1"), and a flat end-cap cylinder of length L-$2a$ (labelled "Urick asymptotic 2"), obtained by replacing L with L-$2a$ in the expression for $TS_{Urick.}$ The latter approximation matches closely the TS for the hemispherically end-capped cylinder for most of the frequency band, with some minor differences appearing at the lower frequencies.

The TS for a plane wave incident onto the rigid cylinder from end-on is shown in Fig.3. Overall, the backscattering and forward scattering levels are lower than for the broadside case because of the smaller portion of the target surface being illuminated directly by the incident wave. In this case, the backscattered target strength is approximated well over most of the frequency band by the high frequency limit of the TS of a perfectly rigid sphere [1], which is given by $TS_{Sph}=10\ \log_{10}(a^2/4) = -26$ dB (labelled "Urick sphere"). As the frequency increases, the forward scattering TS agrees closely with the asymptotic expression for the TS of a perfectly rigid sphere in forward scattering direction [4], which is given by $TS_{Sph\ Fwd} = 10\ \log_{10}(a^2/4\ (1+k^2a^2))$. The values of $TS_{Sph\ Fwd}$ are represented by the curve labelled "Sphere forward asymp."

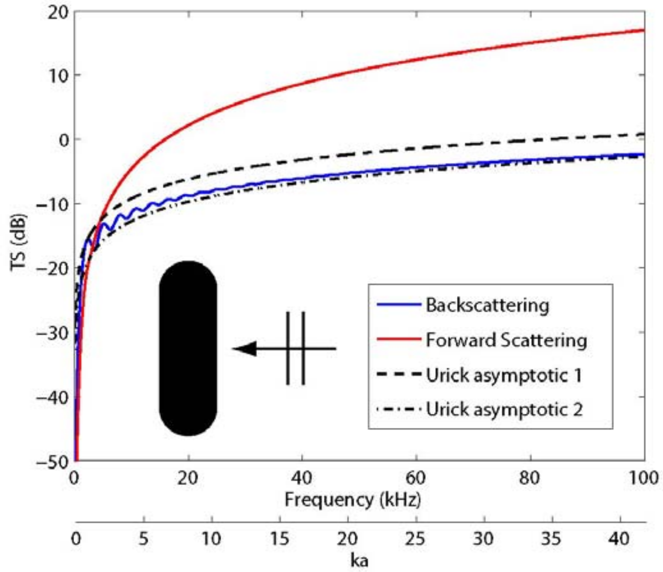

Fig. 2: Perfectly rigid cylinder at broadside incidence.

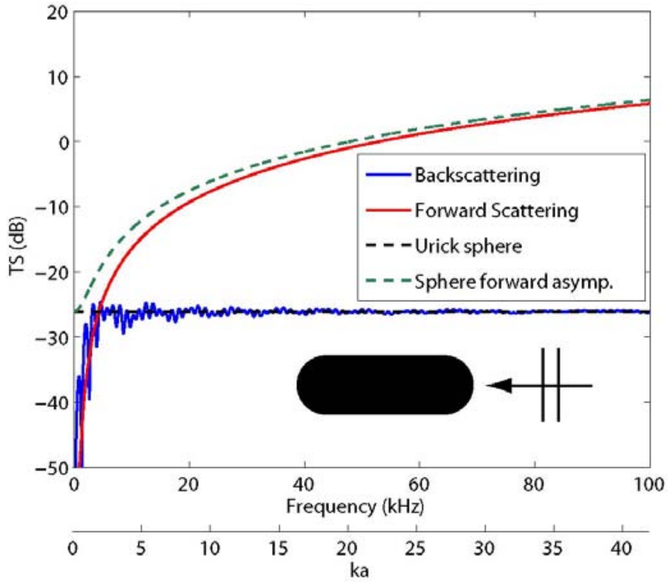

Fig. 3: Perfectly rigid cylinder at end-on incidence.

2.2. Perfectly Soft Cylinder

The target of Fig. 1 is assumed to be perfectly soft, *i.e.* zero total pressure boundary conditions are applied at the interface between the cylinder and the surrounding water. The TS for the perfectly soft cylinder illuminated from broadside is shown in Fig. 4. In this case, the backscattered TS is approximated well by the asymptotic expression for a perfectly rigid cylinder with flat end-caps. The forward scattering TS is approximately 1dB higher than the forward TS of the perfectly rigid cylinder (Fig. 2) at the high end of the frequency band, with the difference between the two levels becoming substantially larger at the low frequencies.

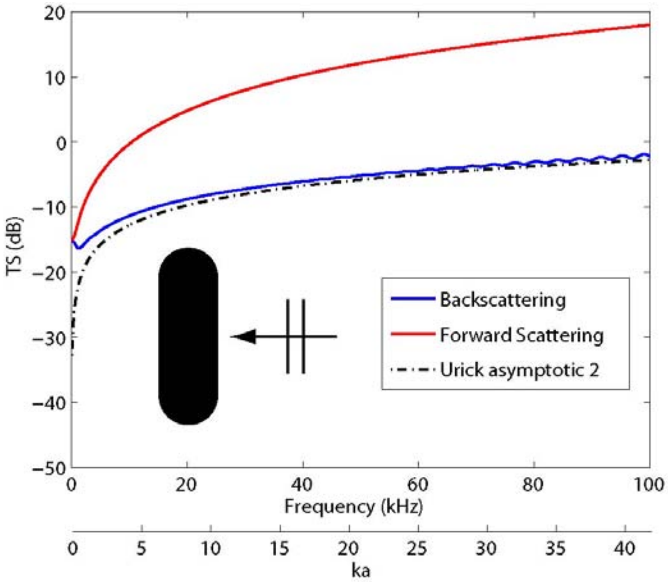

Fig. 4: Perfectly soft cylinder (cavity) at broadside incidence.

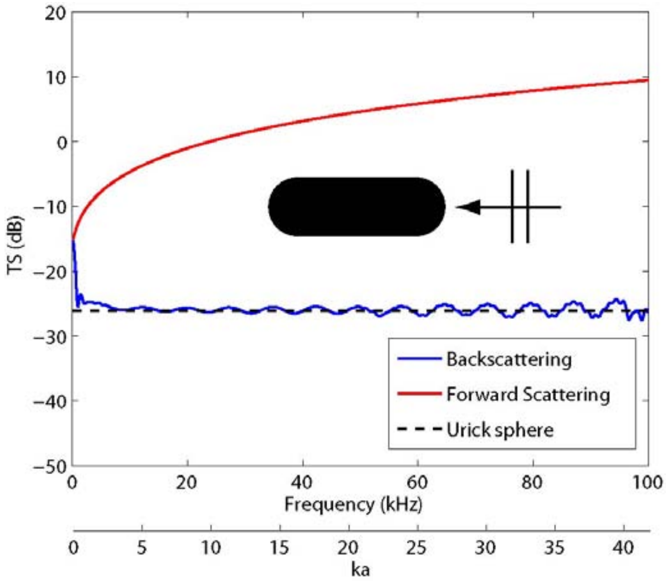

Fig. 5: Perfectly soft cylinder (cavity) at end-on incidence.

The TS for the perfectly soft cylindrical cavity at end-on incidence (Fig. 5) is close to the asymptotic value of -26 dB for the perfectly rigid sphere over most of the frequency band. The steeply decaying trend at the low frequencies is in agreement with the backscattering function of a soft sphere discussed by Bowman *et al.* [5]. The forward scattering TS is overall slightly higher than in Fig. 3.

2.3. Steel Cylindrical Shell of Variable Thickness

The steel cylinder of variable thickness drawn in Fig. 1 is considered in this example. The shell is modelled as a steel layer, with the material parameters being density ρ^S=7700 kg/m^3, compressional sound speed $c^S{}_p$=5950 m/s and shear sound speed $c^S{}_s$=3240 m/s.

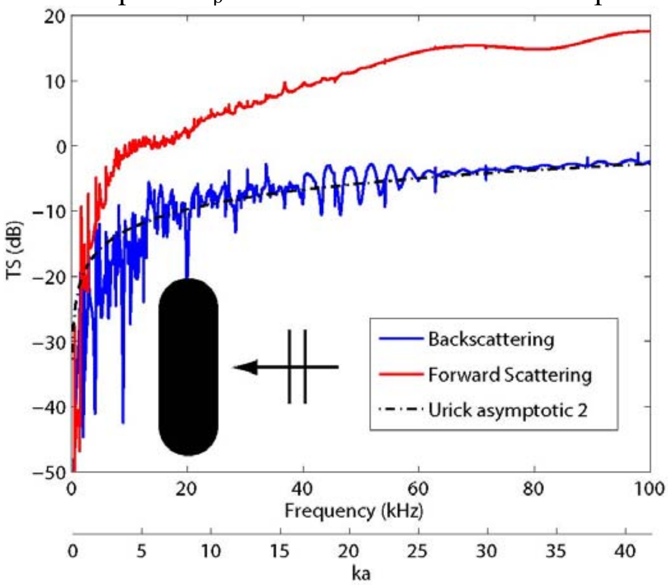

Fig. 6: Steel scuba tank at broadside incidence.

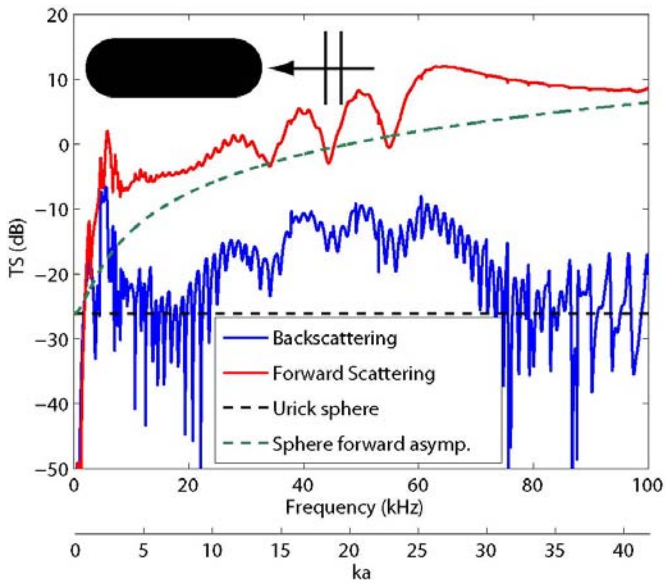

Fig. 7: Steel scuba tank at end-on incidence.

Material damping is neglected in this case. This assumption is justified for steel at low to mid frequencies. On the other hand, one can generally expect that sharp and narrow resonance peaks are smoothed out and that the mean TS levels decrease by some amount as a consequence of material damping at the higher frequencies.

The TS for the steel cylinder illuminated by a broadside incident plane wave is plotted in Fig. 6. In this case, the asymptotic curve for the backscattering from a perfectly rigid cylinder with flat end-caps predicts well the mean level of the backscattered TS of the elastic cylinder, with the agreement being very close at frequencies above 60 kHz. Below 60 kHz, the constructive and destructive interference of shell-borne elastic waves causes resonances and anti-resonances, which are evident in the TS curves. The asymptotic approximations for the perfectly rigid body TS of Sec. 2.1 fail in predicting even the average levels at frequencies below 20 kHz.

Figure 7 shows the backscattering and forward scattering TS for the steel cylinder at end-on incidence, compared to the asymptotic estimates for back- and forward scattering from a perfectly rigid sphere. In this case, the shell-borne elastic waves travel along the entire length of the body, giving rise to resonances which are even more evident than those found in the broadside scattering case of Fig. 6. The asymptotic estimates of the TS (curves "Urick sphere" and "Sphere forward asymp.") can be used only to predict the mean levels of the TS at the high end of the frequency band. If one were to introduce material damping for the steel in the model, it can be expected that the sharp resonance peaks in Fig. 7 would be mostly smoothed out as the frequency increases, since the elastic waves travel along the entire length of the target and are hence strongly affected by the damping. In addition to this, also the mean levels would be lower compared to the case with no damping. On the other hand, it can also be expected that some of the broader resonant enhancements visible in the figure would remain, although somewhat damped.

3. CONCLUSIONS

The high forward scattering target strength levels (above 0 dB relative to the amplitude of the incident plane wave for most of the frequency band of interest) are the first common feature which emerges from the results presented above. The coherent superposition of the forward scattered field and the incident field can yield shadow regions in the vicinity of the target in those cases where the forward TS is close to 0 dB, and highlights in those cases where the forward TS is substantially larger than 0 dB [5].

The approximate simple asymptotic expressions for scattering from a rigid sphere and a rigid cylinder with flat end-caps, can be used to obtain rough estimates of the target strength for the perfectly rigid and the perfectly soft cylinder (non resonant air-cavity). In the elastic case, the asymptotic formulae and the perfectly rigid and soft computations are not usable for predicting the TS of the steel cylinder, except for high frequencies at broadside incidence. This suggests that the target strength of objects of interest, such as divers, diver equipment or underwater vehicles needs to be estimated by employing modelling techniques capable of describing complex elastic targets [2].

The effect of damping on the resonance structure of the elastic scuba tank is the subject of ongoing work, in which a fiberglass cylinder of the same geometry as the one sketched in Fig. 1 is studied using material parameters obtained from tank experiments [6]. Pressurized air inside the scuba tank, modelled as a fluid with a sound speed higher than that of air at sea level, should also be included in computations.

In those cases, where the target is near a boundary, such as the sea floor or the water-air interface, interference patterns caused by the interaction between the target echo and the boundary appear in the TS spectrum. Such problems can be solved by computing the far field via the Helmholtz-Kirchhoff integral, with the proper choice of Green's function for the background medium [2, 3, 7].

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