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Coherent effects of flow- and pressure hull of a generic submarine on target scattering in an active sonar performance model

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Since the late eighties the sonar performance model ALMOST for active and passive sonar is under development at TNO. For active detection performance, initially a point target was used, with a single Target Strength value dependent on parameters like aspect angle, based on measurements or other sources. However to day there is a growing demand for TS of ships and wakes with realistic dimensions and characteristics. A generic sub was modelled with additional software routines, as a pixel file. A newly developed time domain model for hull reflection was implemented, also using scattering pixels, assuming multiple scattering with damping in the metal hull layer. Some modelling results of Target Strength computations are shown, for a generic submarine with pressure hull, with aspect angle, frequency and bandwidth as parameters. The modelled Target Strength decreases towards low frequencies due to hull thickness, as known from literature.

1. Introduction

Since the late eighties the sonar performance model ALMOST for active and passive sonar, of TNO Defence Safety and Security, is used for naval operations and studies [1]. For active sonar detection performance, with the REACT module, a point target with a single Target Strength value is applied, based on measurements or other knowledge. Target Strength is dependent on type of ship, aspect angle, and also the used frequency band. Within the Torpedo Defence System Test Bed by TNO [2], which uses ALMOST as acoustic kernel, there is a demand for Target Strength modelling of ships and wakes.

Therefore more precise modelling of target scattering was investigated [3,4], where the target is represented by reflecting pixels in the new REATES module, within ALMOST. Supposing a fictive infinitesimally short emitted pulse for active sonar, the reflection contributions from all pixels are taken into account in the overall Target Impulse Response function, also including the generally present multi path propagation between sonar and target. By means of only one FFT, which is very efficient in computation time, this Target Impulse Response function can be transformed to the frequency domain, where all specific sonar signal processing takes place, similar to real sonar systems.

So far, only targets with a total reflecting outer surface were considered. On one hand, such target modelling will often yield realistic modelling results, as tested with the well-known Target Strength of a flat surface or a rigid sphere [5]. But on the other hand, for frequencies below 1 or 2 kHz, the ship walls will not reflect totally anymore because of the ratio of wall thickness compared with wave length. The wall mass per unit area will become too low for acting as a rigid reflector. Inside the wall there may be air or water, causing specific effects. Those wall effects are observed in practice towards lower frequencies.

So it is interesting to develop modelling that takes into account this wall structure effect of ships. The new idea here is to consider an extra pixel layer at the inner side of the wall. Moreover more inner layers of pixels can be considered representing multiple reflections within the wall. The benefit of such a method will be that again only one FFT is needed for the Target Impulse Response function of the target pixel file, but now extended in this way. Apart from saving computation time, this method can be considered as a time domain model, which could turn out to be much more computationally effective than frequency dependent wall scattering models, in particular for application to the modern ultra wide band sonars.

Before describing the method for addition of extra pixels representing the internal wall reflections, first the formulas for a total reflecting target surface will be given as an introduction.

After the full describing the wall model, some modelling examples are shown, which indicate the effect of wall thickness, for flow hull and pressure hull of a generic submarine.

2. Coherent echo modelling for total reflecting targets

First the pixel model for total reflecting target surfaces will be described shortly here, see also [3]. After this the newly developed modelling of sound penetration into the target hull, by adding extra pixels inwards the target surface, will be described.

A fictive infinitesimally short transmitted pulse travels from the active sonar position towards the target, represented by pixels, with index ***i***, forming the outer surface. Each pixel ***i*** scatters the incident sound, after a travel time $t_{src,i}$, dependent on the location of the pixel in the "cloud", and the target range. The sonar receiver gets the echo signal after a travel time $t_{rec,i}$. The complete arrival time for pixel ***i*** is:

$$t_{arrival,i,m,n} = t_{src,i,m} + t_{rec,i,n} \tag{1}$$

With:

i = pixel index for target representation *m,n*= multipath indices between sonar source respectively receiver and target.

The above expression is explicitly written for multi path propagation. The contribution of pixel ***i*** for path $t_{src,i,m}$, towards target, and path $t_{rec,i,n}$, from target, is added to the Target Impulse Response (TIR) function, taking into account the total delay $t_{arrival,i,m,n}$, but also the strength of the pulse-like contribution. The latter depends on the propagation loss via path *m*, from sonar to target and path *n* for the path back to the receiver. The pixel has the following "Target Strength" for a total reflecting target surface, see [5]:

$$TS_{i,m} = 20\ {}^{10}\log[\frac{d^2 \cos\theta_{i,m}}{\lambda}] \qquad (2)$$

With:

$\theta_{i,m}$ = angle between incident sound and local normal on reflecting surface, at pixel ***i***

Theoretically *m* for the incoming sound can be interchanged here with *n* for the outgoing sound.

The wall model is described now below. The existing programming for the TIR function will be applied here with only minor modifications, by adding some extra pixels to each surface pixel, to model the wall characteristics.

3. Wall reflection model

An example of a pixel file for a generic submarine is shown in Figure 1. The inside pressure hull is shown additionally here. A local part of the target surface is shown in Figure 2, where the sound is supposed to hit this surface from above. Instead of assuming a total reflecting wall surface, in this new model the wall is supposed to possess physical characteristics like material parameters. The density, sound speed and damping per wave length will play a main role in the reflectivity, for instance for an iron ship wall of certain thickness, with air

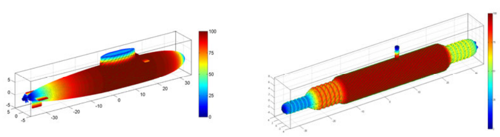

Figure 1 Representation of submarine Target pixel file

or water behind it. The latter case will mainly concern submarine flow hulls. The upper pixel positions, see Figure 2, called "level 0" pixels in the following, are the pixels of the initial target pixel file, to start with. So the "level 0" pixels

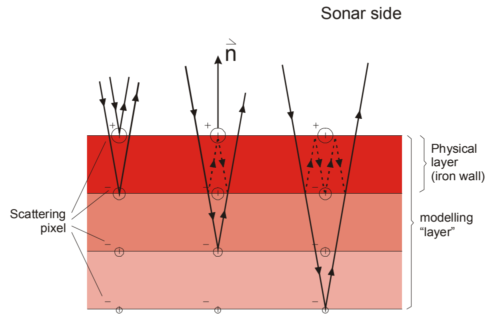

Figure 2 Scheme for new wall pixel modelling in REATES, applied in generic submarine with pressure hull

basically describe the detailed ship construction, shown in Figure 1. In this target pixel file also a local wall thickness figure is added, so in addition to the already mentioned local normal vector per pixel. Mind here that the length of the latter vector is equal to the (small) target area part A, represented by the pixel.

The inside wall boundary is shown in Figure 2, as a so-called "level 1" below the "level 0" surface (the upper wall boundary). Physically, the part of the sound that is transferred through "level 0", will be reflected at "level 1". Because of this transfer of sound through "level 0", also a partly reflection at "level 0" is supposed, this on the contrary to the total reflection assumption in the simple modelling, see Eq.(2). The reflected sound at "level 1", can transfer upward through "level 0", and farther back towards the sonar. This mechanism is accounted for in the model by the extra pixel layer at "level 1" see Figure 2.

Because generally the sound speed in the wall is different from the water, therefore the position of the level 1 pixels is adapted in a way that the travel time between level 0 and level 1 remains valid, see below. Because of the partial reflections at level 0 and level 1, the Target Strengths of these pixels must be taken lower than for total reflecting pixels.

A reflection from level 1 back upwards can also be reflected downward at level 0. After a subsequent second reflection at level 1 upward it can transfer through level 0 back to the sonar. This mechanism is accounted for by a second extra pixel layer at level 2, placed below level 1, see Figure 2. Levels 0, 1 and 2 are taken equidistant. Other temporarily trapped reflections inside the wall are taken into account even by more extra pixel layers, placed at levels 3, 4, 5,…etc. It is plausible that the Target Strength will generally decrease for these lower levels. The TS for all extra pixels will be modelled in detail in the following, as well as the original "level 0" pixel Target Strengths.

The pixels at “level 1”, see Figure 2, are used to model the inner boundary of the wall. Because the level 0 pixels are not any more confining a totally rigid reflector, the Target Strength for these pixels is taken lower than for total reflection.

For convenience, the Target Strength TS per pixel is written as intensity *ITS*. In the case of a total reflective, so rigid surface, we have, [5]:

$$ITS_{tr} = 10^{0.1*TS} = [\lambda/(A\cos\theta)]^2 \qquad (3)$$

With:
A = target surface (part) of pixel

For constituting the TIR function, the complex amplitude must be applied in REATES, where also the sign is of importance:

$$Ampl_{tr} = 10^{0.05*TS} = \lambda/(A\cos\theta) \qquad (4)$$

The intensity reflection coefficient IR_{up} at “level 0”, is taken as the well-known result for plane wave reflection [6]. It is computed close to normal incidence, as a practical choice, and is dependent on mechanical and acoustic material parameters for the wall, like density, sound speed, and damping per wave length, and the same parameters for water. The TS for the “level 0” pixels is decreased with this reflection factor, as follows:

$$ITS_0 = ITS_{tr} \cdot IR_{up} \qquad (5)$$

With:
ITS_0 =TS for “level 0” pixel layer
IR_{up} = intensity reflection coefficient; level 0

The intensity reflection IR_{in} at the inside of the wall, at “level 1”, is modelled again with the plane wave result [6]. The extra pixel layer of “level 1” of strength ITS_{i1} is as follows:

$$ITS_1 = ITS_{tr} \cdot IR_{in} \cdot \delta^2 \cdot \tau^2$$
$$\tau = 1 - IR_{up}$$

Where:
δ = single path intensity damping in layer
τ = transmission intensity ratio through wall boundary

The transmission intensity ratio τ into the wall is based on the energy balance assumption, which is quite valid for the propagating sound considered here [6]. Mind that IR_{in} can differ from IR_{up}, because most ship constructions will be air-filled. An exception here is a submarine flow hull, where water is inside. Because the pixel scattering must be able to describe the outer reflection and all internal wall reflections, the “level 1” pixels are placed at a distance Δ_p in the opposite direction of the local normal vector (on the local surface):

$$\Delta_p = \Delta \cdot c_{water} / c_{wallmaterial}$$

Where:
Δ = the actual wall thickness

This corrected thickness Δ_p assures correctly modelled time delays for the level 1 pixels, for use in the TIR function. Subsequently “level 2” pixels are constructed to represent double reflection inside the wall, placed at Δ_p below level 1, see Figure 2:

$$ITS_2 = ITS \cdot IR_{up} \cdot IR_{in}^2 \cdot \delta^4 \cdot \tau^2$$

In the same way level 3 and higher can be constructed:

$$ITS_3 = ITS \cdot R_{up}^2 \cdot R_{in}^3 \cdot \delta^6 \cdot \tau^2$$

As mentioned above, the TIR function requires the complex amplitudes of the pixels, see Eq.(4), summarised now from the above:

$$Ampl_0 = Ampl_{tr} \cdot R_{up}$$

$$Ampl_n = -\frac{\lambda}{A\cdot\cos\theta} \cdot R_{in} \cdot \delta \cdot \tau \cdot \left(R_{up} \cdot R_{in} \cdot \delta\right)^{n-1}$$

(n=1,2,3..)

By using:
$R_j = \sqrt{IR_j}$ (“j”=”up”: level 0, or “in”: level 1)
IR_j, R_j = intensity resp. complex amplitude reflection coefficient.

Mind that all extra pixels, so “level 1” and higher, are acting in counter phase, indicated by a minus sign. This is due to the reflections inside the wall.

All amplitudes can be added in phase:

$$\sum_{n=0}^{\infty} Ampl_n = \left(R_{up} - \delta \cdot R_{in}\right) / \left(1 - \delta \cdot R_{up} \cdot R_{in}\right) \qquad (7)$$

If R_{up} and R_{in} are equal, which is the case for a flow hull of a submarine, where water is also at the inside, then for a wall thickness approaching zero, so with δ towards 1, no amplitude will remain in Eq.(7), which looks acoustically consistent.

In the following part some examples are given for a generic submarine where wall thickness, wall materials and frequencies are varied.

4. REATES results of modelled echoes for a generic submarine

REATES was run for a shallow water scenario with a generic submarine, already presented above, see Figure 2. The above described wall model is used in this submarine, applied with water behind the flow hull, and air inside the pressure hull. The target range is 10 km, with a target aspect angle of 60^0. A generic active towed array sonar is applied in the REATES modelling. Two pulses are chosen, with centre frequencies 1500 and 500 Hz, and with band widths of 1000 and 200 Hz, respectively. Computations are made including multi path propagation, for realistic hull thickness values of the submarine, see Figure 3.

The upper part shows a complicated echo structure, which is grace to the wide band of 1000 Hz. The horizontal axis is active sonar range, being a time scale converted in a linear way using half the average sound speed. The lower part shows a similar echo structure but less detailed due to the smaller band width of 200 Hz.

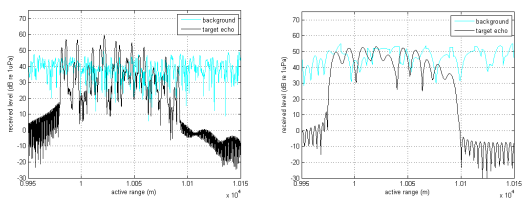

Figure 3 REATES result with echo structure and reverberation background, including multi path propagation; left) sonar pulse 1500 Hz with 1000 Hz band; right) pulse 500 Hz with 200 Hz band

This same submarine can also be modelled with the assumption of "total reflecting" pixels for a total reflecting target surface. Comparisons of results for this total reflective submarine and the submarine with realistic wall thickness are shown in Figure 4 and Figure 5. For simplicity only the strongest propagation path is taken here.

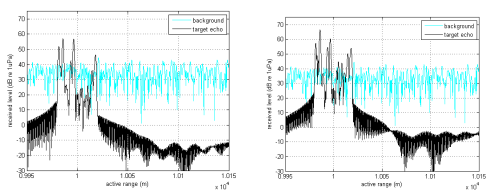

Figure 4 REATES result with echo structure and reverberation background; sonar pulse 1500 Hz with 1000 Hz band; left) realistic hull; right) total reflecting target structure

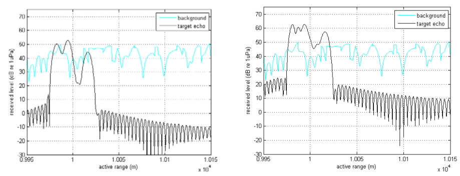

Figure 5 REATES result with echo structure and reverberation background; sonar pulse 500 Hz with 200 Hz band; left) realistic hull; right) total reflecting target structure

Obviously the total reflective (fictive) submarine turns out to show higher echo levels.

For the above scenarios, an "effective Target Strength" figure can be computed: The real submarine target is replaced by a point target with known Target Strength TS. The modelled echo output is compared with the echo output for the submarine target, by means of a maximum filter applied to both modelling results. Then the "effective Target Strength" is simply computed from the dB difference of both "maximum filter" outputs.

The Target Strength is computed in this way, for one single propagation path as well as for 5 paths in the scenario, see Table 1. TS values for the realistic submarine with wall thickness turn out to be around 10 dB lower, compared with the simple assumption of a total reflective target surface. Of course this difference will be considerably dependent on frequency and aspect angle.

	Realistic hull	*Total reflecting*
F=1500/B=1000 Hz/ 1 path	2 dB	12
F=1500/B=1000 Hz/ 5 paths	4	13
F=500/B=200 Hz/ 1 path	-3	6
F=500/B=200 Hz/ 5 paths	-7	5

Table 1 Target Strength of generic submarine based on maximum detection filter

Finally the Target Strength is computed versus aspect angle, for both pulses, see Figure 6. The 500 Hz pulse shows considerably lower TS levels compared with the 1500 Hz pulse. This effect is ascribed to the effect of the hull thickness.

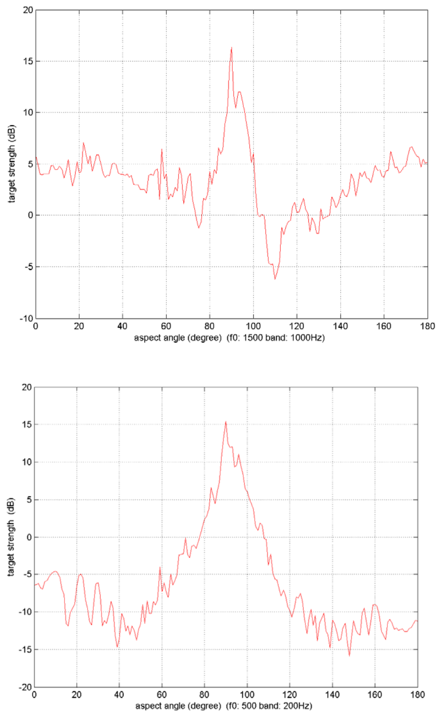

Figure 6 Target Strength versus aspect; upper) pulse 1500 band 1000 Hz; lower) pulse 500 band 200 Hz

Finally it must be remarked that validation of these modelling results with measured Target Strength data remains an important item for future work.

5. Conclusions

This paper presents a newly developed hull reflection model, applicable to technically specified submarines. Dimensions and thickness of all submarine parts is input for the model.

The model is implemented as a new feature in the ALMOST REATES target echo model of TNO. REATES models detailed target echo structures, basically versus arrival time, and was built in the last years as a further development of REACT, the active sonar performance modelling in ALMOST, using the programmed active sonar equation.

REATES is able to model Target Strength values for extensive specified ship targets, where these figures can be used operationally on board of ships in ALMOST/REACT. The presented hull reflection model yields more realistic and reliable results from REATES, in particular for the low frequency active (LFAS) sonars.

The effect on Target Strength of the local hull thickness of submarines in general, is expected to be much dependent on aspect angle and frequency. This study shows Target Strength differences around 10 dB down, compared with the simple assumption of a total reflective submarine target.

Further validation of the modelling results versus Target Strength measurements, however, remains an important item in the future.

References

[1] P. Schippers, "The ALMOST PC model for propagation and reverberation in range dependent environments", *Proceedings of UDT Europe, 1995*

[2] F.P.A. Benders, "Torpedo and countermeasures modelling in the torpedo defence system testbed", *Proc. of the European UDT 2004 Conference*

[3] P. Schippers, "Coherent target scattering in the active sonar performance model ALMOST/REACT", *Proceedings of ECUA 2004*

[4] P. Schippers and S.P. Beerens, "Echo structures and Target Strength modelling for a synthetic submarine", *Proc. of the European UDT 2007 Conference*

[5] R.J. Urick, "Principles of Underwater Sound", *McGraw-Hill Book Company, New York,* 2nd ed. 1975

[6] M.A. Ainslie and P.W. Burns, "Energy-conserving reflection and transmission coefficients for a solid-solid boundary", *J. Acoustic Soc. Am. 98 (5),*2836-2840 (1995)