COMPARING TARGET ECHO STRENGTH MODELS OF A GENERIC SUBMARINE

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Abstract: *Thales UK carries out work associated with the underwater acoustic signatures of a variety of platforms, with typical dimensions ranging from a few metres to hundreds of metres, and covering frequencies from a few Hz to hundreds of kHz. Supporting these projects is a comprehensive target echo strength capability, including in-water test facilities and modelling tools. This paper discusses some of the different types of model available to calculate the target echo strength of underwater objects.*

Modelling tools are used for different purposes ranging from initial concept - stage design through to more detailed assessments of specific signature features and signature reduction measures. The models employed include analytic models based on simple, rigid geometric shapes; models for complex rigid bodies based on geometric optics methods; physical optics models for elastic bodies; and finite element analysis for arbitrary elastic bodies. The tools can be applied at differing levels of complexity and fidelity to detail, and may assume perfect reflection or utilise a full elastic solution. The use of these models is discussed, and the paper also describes a number of methods for representing the target echo strength predictions, including graphs of aspect - dependent integrated echo intensity; "hourglass" plots of echo intensity as a function of time of arrival and aspect; and frequency - azimuth plots.

The use of these modelling tools is demonstrated with the aid of particular examples, and results are presented for the predicted target echo strength of the BeTSSi generic submarine, which was the subject of an international collaborative workshop at The Hague in 2016. The paper discusses the differences between the predicted results from the various models, and considers the significance of these differences when selecting methods and applying the tools at different frequencies and for different purposes.

Keywords: *Target Echo Strength, submarine, BeTSSi, modelling*

1. TYPES OF TARGET STRENGTH MODEL

Many workers have practical reasons for wishing to predict and understand the acoustic Target Echo Strength (TES) of objects in water; modelling tools are used for different purposes and at different stages in the development of systems. Different tools are employed to provide predictions at differing levels of complexity and fidelity to detail appropriate to the needs, which may range from exploration of major parameters at the stage of initial concept studies, to detailed models of specific structures used in the assessment of final designs.

1.1. Empirical models

In the initial stages of a project, estimates may be obtained from empirical relationships such as the general trend of TES against displacement derived from a body of measurements or model results. Alternatively, a comparison with a similar target with known TES may provide a good basis for estimation.

1.2. Analytic Solutions.

The TES of any rigid body of canonical shape can be computed exactly by solution of the wave equation with the relevant boundary conditions at the target surface in a suitable coordinate system. This is only practicable for simple shapes; exact solutions exist for a sphere and a cylinder, but other closed form solutions can be obtained as approximations, valid under specified conditions such as the solution for an arbitrarily curved convex surface with large radii of curvature [1] (where “large” means with respect to the acoustic wavelength). Formal methods have also been used to derive analytic solutions for some more complex objects formed from the combination of primitive shapes (e.g. a cone-sphere) where appropriate conformal transformations can be identified, but these have limited applicability in TES problems. One way in which the analytic solutions (exact or approximate) can be used to address real-life scattering problems is by creation of a model representing the target as a combination of simple shapes, and combining the scattered pressures from each shape calculated separately [2]. This method neglects the influence of the “missing” surfaces in the solution for each primitive shape and no formal treatment of the errors introduced by the method seems to have been published, but the technique allows a rapid determination of the relative importance of different parts of the target. Thales UK has developed the THREBITS modelling tool utilising this approach and successfully used it in the early design optimisation studies of a number of underwater systems. This tool provides results quickly, and therefore permits the exploration and comparison of the TES of a range of geometries.

1.3. Geometric Acoustics

Geometric acoustics or ray methods are applicable where the target dimensions are much greater than the acoustic wavelength; the scattered field can be represented as an expansion in terms of inverse frequency, in which the first term is the geometric acoustics result. The basis of the method is the computation of the range of angles over which a bundle of rays (assumed to be parallel when approaching the target) is spread after reflection – each ray being reflected at the angle given by the law of reflection. The number of scattered rays passing through a unit surface in a given direction gives the scattered field pressure in that direction. Modelling tools using this method can deal with complex target geometries including re-entrant or concave surfaces and have relatively short computation times, making this the method of choice for high frequency solutions and reverberant cavities. The target is considered to be a purely passive geometric object and there is no consideration of effects due to the dynamic response of the scatterer. In many applications, this is an adequate approximation - for example when modelling a submarine clad with pressure-release tiling. The effects of absorption can be approximated by inclusion of an appropriate reflection coefficient at the surface, which may be dependent on the angle of incidence. The basic ray tracing approach allows only specular reflection and predicts hard shadow edges. The use of a finite number of rays means that some reflection paths will always be missed, and the method tends to be inaccurate over regions where the scatterer has high curvature. There is no way to determine the number of rays needed to achieve a given accuracy; in spite of these limitations, comparisons between ray model results and exact solutions often indicate better agreement than the underlying assumptions would suggest [3].

1.4. Physical Acoustics extensions to Geometric Acoustics Models

Ray theory does not describe phenomena such as interference and diffraction, and fails to account for the presence of a scattered field in a shadow region where there is no direct line of sight, which can be accounted for by energy scattered or diffracted at the target surface. Physical acoustics methods take into account these phenomena and thereby improve the predictions, particularly at lower frequencies. Some physical acoustics models add second-order terms to the geometric acoustics result to represent the effects of diffuse reflections. A common approach is to launch rays in non-specular directions with the overall spatial distribution of energy obeying Lambert’s Law, with the amplitude described by effective scattering coefficient. Diffraction arises where incident rays strike edges, resulting in a distribution of energy in a range of directions; or are at grazing incidence to surfaces, resulting in the generation of creeping waves which follow the surface. Various laws of diffraction are used to characterise the diffracted rays, including the Geometrical Theory of Diffraction (GTD) [4]. This introduces additional rays using diffraction coefficients determined from canonical problems such as the infinite wedge. The GTD allows for propagation around obstacles and into shadow zones, but fails near reflection and shadow boundaries. This is overcome by the Uniform Theory of Diffraction [5] through the use of transition functions that provide for a continuous and bounded diffracted field.

1.5. Tangent Plane Approximations

Kirchhoff / Tangent Plane (KTP) approximation methods solve the Helmholtz-Kirchhoff integral by dividing the target surface into a mesh of plane elements or facets. Using the Kirchhoff approximation, the pressure and particle velocity on each element are approximated with the values that would exist if the surface was infinite in extent. The reflection from each element can then be found analytically and the TES of the surface can be calculated as the coherent sum of the contributions from the individual elements. The method can be applied to rigid surfaces, or angle-dependent reflection coefficients may be applied to represent real materials. Advantages include rapid execution times even with complex geometry; the disadvantages include the treatment of the surface as a purely passive scatterer, without fluid/structure interaction effects such as resonances, and the lack of edge diffraction effects. The method is less accurate for bistatic TES, particularly forward scattering, because the assumption is made that the acoustic pressure is zero on all elements of the surface in the shadow zone on the far side of the target from the source. Thales UK has implemented this approach in the SCATTER model which incorporates approximate methods for bounding the TES resulting from penetration of surfaces and subsequent scattering.

1.6. Numerical solutions of the wave equation

Both boundary element (BE) and finite element (FE) methods have been applied to develop numerical solutions for the TES. FE uses elements to discretise the entire domain leading to harmonic solutions of the wave equation with the relevant boundary conditions. BE discretises the scattering surface and solves the Helmholtz-Kirchhoff integral equation; the solution in the fluid domain can then be obtained by integration over a surface. In both methods the necessary discretisation is dependent on the frequency, rather than the geometry, and in FE a sufficient volume of the fluid domain must be meshed to avoid near-field effects. BE methods avoid the need to mesh the domain but are more computation-intensive for a given number of nodes. Both approaches are thus restricted to comparatively low frequencies by the computation time and memory requirements. Care must be taken when using commercial general purpose FE packages for underwater TES calculations because approaches typically taken to reduce computation overheads, which may be acceptable to the majority of users, are not necessarily appropriate to modelling of highly fluid-loaded elastic structures. For this reason, Thales UK prefers to utilise codes such as PAFEC and the proprietary tools FELINE and SuperFELINE which were developed specifically for applications involving fluid loaded structures.

2. THE BETSSI SUBMARINE TARGET

This paper demonstrates the use of some of the models available to Thales UK, using the example of the Benchmark Target Strength Simulation (BeTSSi) generic submarine model which was the subject of a collaborative workshop at The Hague in 2016 comparing the predictions of different models from a number of teams. The BeTSSi Submarine definition was developed by FWG in Germany [6] and was designed to facilitate an international workshop held at Kiel, Germany in 2002 [7] to compare numerical codes for prediction of TES. The model is a simplified generic representation of a typical diesel-electric submarine of around 1700 Tonnes displacement, with the external geometry simplified to ease the creation of input descriptions for different models, and with limited internal structure – in particular, rib stiffeners and internal decks are omitted. The model does however include a representation of free-flooded regions containing structures including bulkheads and decks, torpedo tubes and a sonar flat in the bow area and a variety of simple structures in the fin. The external form of the model and the internal components are shown in Fig. 1.

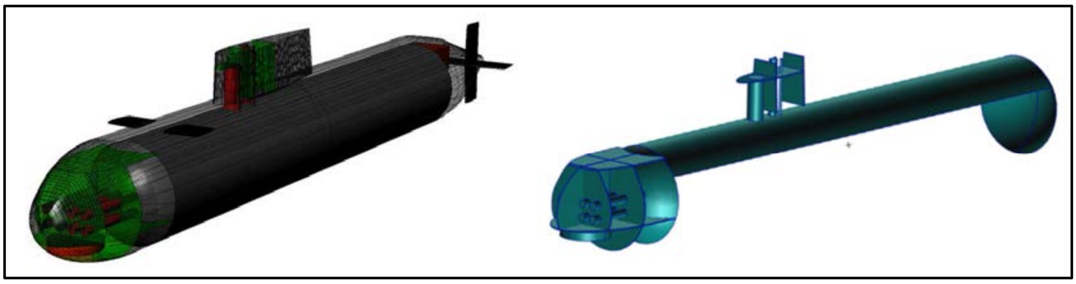

Fig. 1: The BeTSSi submarine model. Left: overall view, right: internal structures.

3. BETSSI MODEL RESULTS

3.1. Analytic model: THREBITS (with simplified geometry)

The first result shows the prediction by the Thales THREBITS tool, using a hemi-ellipsoid, cylinder and truncated cone, surmounted by a vertical ellipsoidal cylinder, to represent the BeTSSi submarine external form. The individual TES contributions from these elements have closed-form results which are computed and added coherently to produce the results shown in Fig. 2. The contribution of the individual elements can also be assessed; for example, the contribution of the hemi-ellipsoid element representing the bow is shown. The THREBITS model does not require any surface generation and meshing and this makes it cheap to run to compare different hull forms. For example, the overall length can be increased, resulting in a stronger broadside TES peak and movement of the tail-cone peak as shown (at lower angular resolution) in the upper right plot of Fig. 2. The THREBITS model can also provide bistatic predictions, by utilising more elaborate equations; sample bistatic results are also shown in Fig. 2.

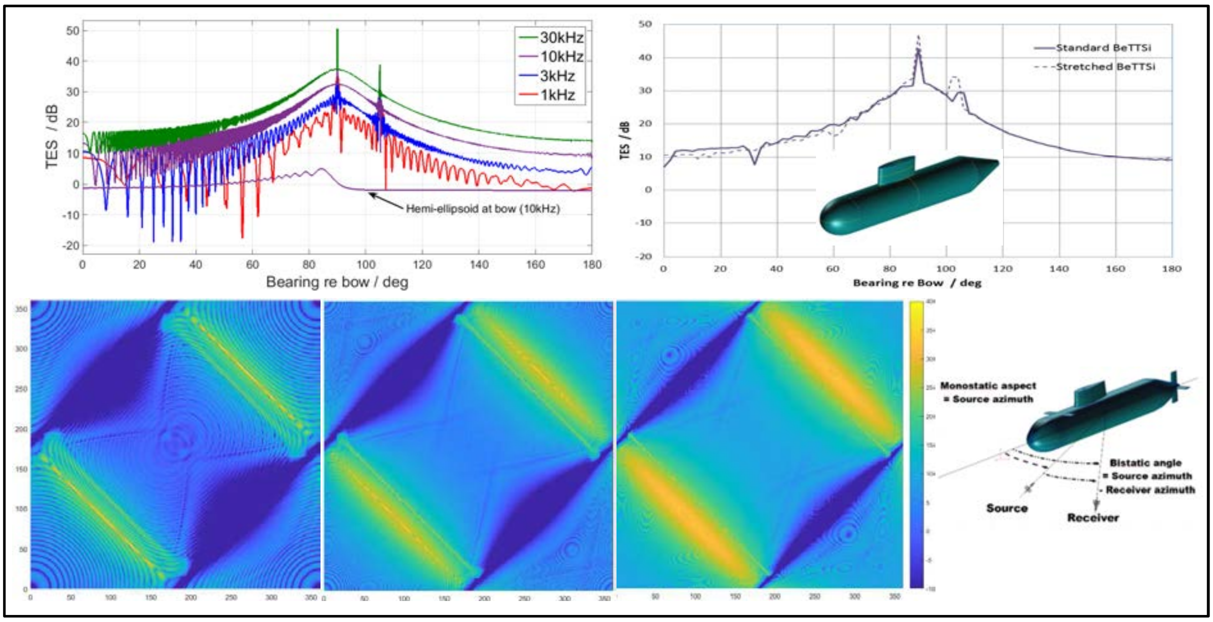

Fig. 2: Analytic THREBITS TES predictions for a simplified BeTSSi submarine model. Upper left: monostatic TES prediction; upper right: effects of changing length (10kHz); inset: simplified model. Lower: bistatic TES prediction (ordinate: receiver angle; co-ordinate: source angle); left: 1kHz; centre left: 3kHz; centre right: 10kHz; right: angle definitions.

Analysis of these results demonstrate that the largest peaks in the TES are generated by the beam-on reflection from the cylindrical section and the reflection from the tail cone at the cone semi-angle. Comparison with the plots for individual components shows that the fin dominates over most of the azimuthal range. For example, at 10kHz the hemi-ellipsoid at the bow contributes just -1dB at 0 deg (bow-on) rising to a maximum of 5dB at 90 deg. At angles in the bow quarter (between 0 deg and 90 deg), the combination of the reflections from the front of the hemi-ellipsoid and the leading edge of the fin results in interference fringes. In the aft quarter, such fringes are only evident at the lower frequencies as at higher frequency the tail cone response is confined to a narrow range of angles. Note also that the truncated cone was not terminated by a disc so there is no strong reflection at 180 deg.

3.2. Tangent Plane Model: SCATTER (with simplified geometry)

The simple analytic THREBITS model results shown above can be compared with the results of a KTP model of the same geometry (with the exception that here the tail cone is closed at the end), calculated using the Thales SCATTER model (Fig. 3).

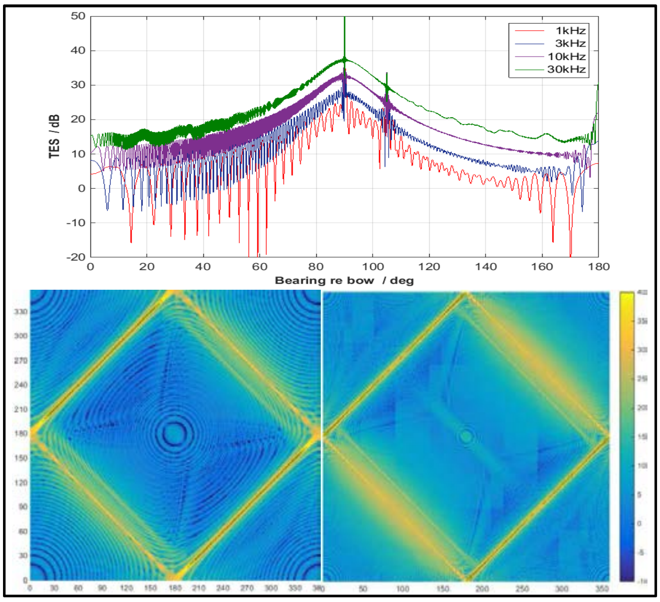

Fig. 3: SCATTER TES predictions for the simplified BeTSSi submarine model. Upper: monostatic TES. Lower: bistatic TES (axes as Fig. 2); left: 1kHz; right: 3kHz.

Apart from the features close to stern-on which are associated with the closure of the tail-cone, the broad characteristics of the results (Fig. 3) are the same although at the highest frequency the result shows some ripples which are an indication that a finer mesh geometry is required to ensure the facet representing the local surface reflects with the correct phase.

3.3. FE Model: SuperFELINE (axisymmetric approximation)

In the Thales SuperFELINE model the solution is decomposed into circumferential Fourier modes which allow more rapid solution for axisymmetric structures. Fig. 4 shows results of a prediction for an axisymmetric representation of the BeTSSi submarine.

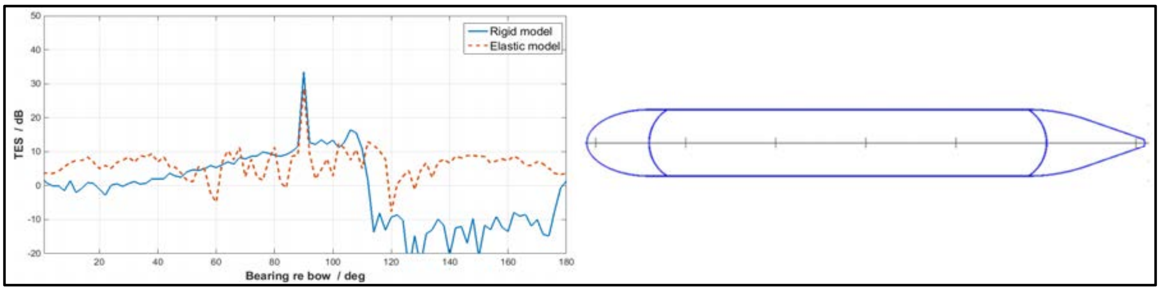

Fig. 4: SuperFELINE predictions for an axisymmetric representation of the BeTSSi submarine model. Left: TES at 1kHz; right: the model geometry.

The example results in Fig. 4 have been computed at reduced angular resolution and show the difference between the TES of a rigid structure and a fully elastic structure. Where applicable, this method shows features associated with resonances and modal behaviour, and in the example the effects of penetration through the outer casing are clearly seen.

3.4. Tangent Plane Model: SCATTER with true geometry

The SCATTER model uses the KTP method and can be applied to arbitrarily complex geometry, and this section gives results for a SCATTER model of the true BeTSSi geometry as defined in Fig. 1. The Thales implementation of the method includes an approximate treatment of acoustic penetration by calculating the average transmitted intensity through the outer surface, followed by scattering by any underlying structure. Fig. 5 below shows the SCATTER result for the true BeTSSi true geometry with both rigid boundaries and realistic elastic boundaries, resulting in transmission into internal spaces.

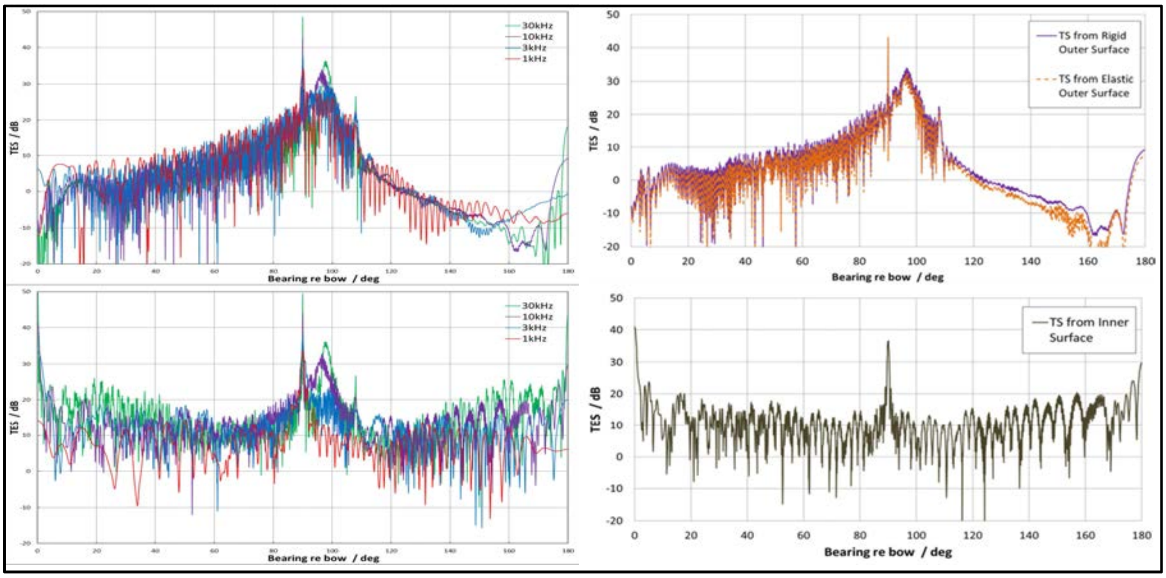

Fig. 5: SCATTER predictions for an exact BeTSSi submarine model. Upper left: rigid boundaries; upper right: TES from outer surface only at 10kHz, rigid and elastic. Lower left: resultant TES for full elastic model; lower right: TES from inner structure at 10kHz.

The major differences between these results and the earlier results for the simplified geometry arise from the more accurate representation of the fin – using the true NACA geometry rather than an ellipsoid results in an asymmetric TES with a peak around 97 deg, and significantly lower levels in the stern quarter. The simpler model is however shown to be sufficiently accurate for many purposes. The addition of penetration effects produces new peaks, notably at 0 deg and 180 deg attributed to internal bulkheads, and significantly higher levels elsewhere due to the complex internal structure.

The SCATTER model also allows results to be presented in other formats, which can be useful aids to understanding the TES. Fig. 6 shows an “hourglass” or downrange plot which shows the time of arrival of each part of the reflected signal. The plot has been annotated to show which part of the structure gives rise to each reflection. Also shown is a frequency-azimuth plot which shows the dependence of TES on frequency, an elevation-azimuth plot which shows the TES in two dimensions, and a phase map which shows the relative phase of the signal contributions from various parts of the target. The elevation-azimuth plot and phase map both highlight the significant reflection from the fin at small elevation angles.

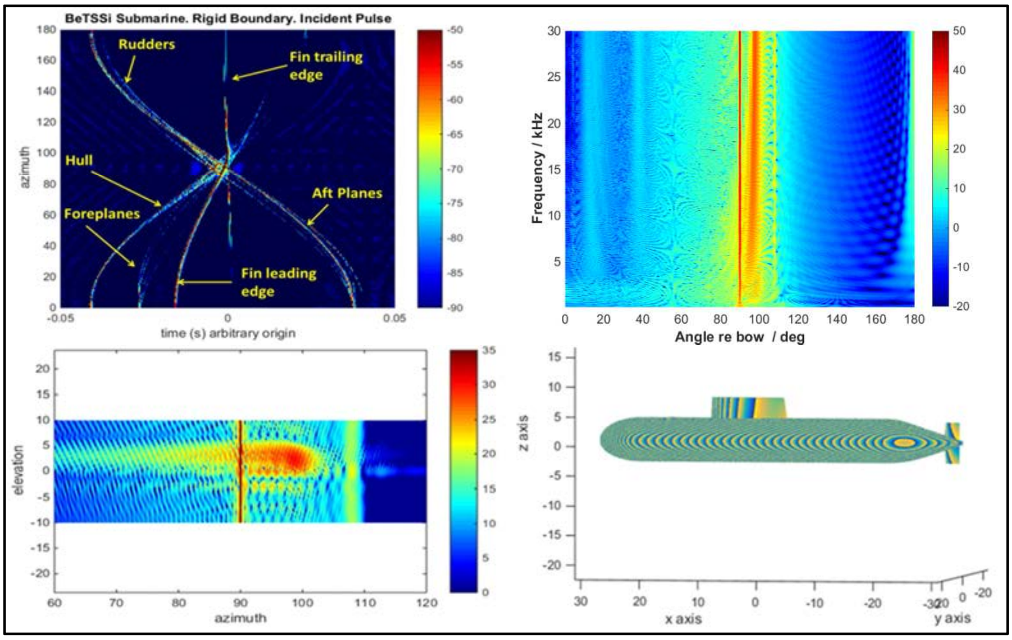

Fig. 6: Other representations of SCATTER predictions. Upper left: downrange plot for rigid model; upper right: Frequency-Azimuth plot for full elastic model. Lower left: Elevation-Azimuth plot; lower right: phase map (100 deg azimuth, 2.5 deg elevation, 3kHz).

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