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# APPLICATION OF THE NUMERICAL METHOD OF FUNDAMENTAL SOLUTIONS FOR FISH TARGET STRENGTH ESTIMATION

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## Abstract

Target strength (TS) is one of the most important magnitudes in acoustic surveys for fish populations and biomass monitoring. Many numerical models have been developed to calculate the scattering of fish, and mainly, of air swimbladder. All these methods provide the TS value in the far field region. In this work we validate the application of the method of fundamental solutions (MFS) comparing the TS calculations for a prolate-spheroid swimbladder using MFS with the calculations from the most relevant and well- established models used for TS modelling. MFS is a mesh less method, and it applies successfully to calculate TS at the high frequencies used in active underwater acoustics, diminishing the calculation costs. The influence of fish bone, for dorsal (down-looking) or ventral (upward-looking) echosounder measurements, is analyzed using MFS for TS calculations. The evolution from near to far field region has been also studied using MFS, providing a useful prediction for the proper working distance for fish TS measurements in ex-situ experiments or in aquaculture monitoring applications.

**Keywords:** target strength, numerical methods.

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## 1 Introducción

Target strength (TS) is one of the most important inputs in active underwater acoustics [1]. TS refers to the ability of a target to return an echo and it is a measurement of the acoustic reflectivity of the target. TS value depends both on the object properties and the acoustic frequency, and it is a fundamental magnitude to identify or characterize an underwater target. In fisheries, TS measures the acoustic reflectivity of the fish and it is depending on variables such as species, size, shape, orientation, depth and acoustic frequency and it is one of the most important inputs to study acoustically fish populations [2]. In aquaculture, TS has been proposed to monitor the fish growing in floating cages, as well to control the intrusion of predators in the cage [CITA 3]. The main contribution to the TS value in fish comes, when it is present, from the swimbladder. Swimbladder is a gas filled organ present in many species, used for regulating buoyancy and to emit and receive sound and shows a very high impedance contrast with water and fish tissues, dominating the acoustic scattering from fish [4].

Many acoustic scattering models have been applied to estimate fish TS, in order to provide a tool for understanding TS variations with species, size, shape, depth, orientation or frequency parameters. TS calculations are also fundamental tools for interpreting experimental results in ex-situ an in-situ TS measurements. A very strong effort has been done for simulating the scattering of gas-filled swimbladders, which are considered to reflect as a soft surface. A comparison of the results obtained using well stablished numerical models was developed in [5]. It considers the acoustic reflection of pressure release prolate spheroids, which approximate a fish swimbladder, and compares the result obtained from the analytically exact prolate-spheroid-modal-series model (PSMS) with the computed results from Kirchhoff-approximation (KA) and Kirchhoff-ray-mode (KRM) scattering models and from the Helmholtz equation solution using finite elements (FE). Details can be obtained in [5] and references therein.

In this paper we provide a validation of the method of fundamental solutions (MFS) [6,7] for TS calculation. We compare the results obtained for the calculation of the scattering of gas-filled prolate spheroids from MFS with the results from PSMS, KA, KRM and FE models published in [5]. MFS is a mesh less method. It provides two main advantages respect other numerical methods. First, the high values of working frequencies in TS measurements (18-700 kHz) implie high computational costs due to the need of very fine mesh and therefore long calculation times. This problem can be avoided using mesh less methods as MFS. Second, most of the numerical methods provide scattering results only in far-field region of the target. It is useful when we work at large distances, but when we work at short or middles distances, as is the case of aquacultures cages or very large fish close to surface, it is necessary to understand the near-to-far field transition to interpret the experimental measurements [7]. The evolution of TS value from near to far field regime is also evaluated in this paper using the MFS method. We have calculated the scattered acoustic field corresponding to a schematic fish model, formed by the fish bone and the gas-filled swimbladder, and we show the TS evolution with distance and fish orientation.

## 2 Methods

We have calculated backscatter TS from gas-filled prolate spheroids with semi-major axis [m] and semi-minor axis [m] using the MFS method. We have considered a range of incident acoustic wave angles in order to compare with [5]. TS has been normalized to prolate spheroid dimension. We have defined a length-normalized TS as $nTS = 10\ log_{10}\ (\sigma_{bs}/^{2})$ [dB] where $\sigma_{bs}$ [m$^2$] corresponds to the cross-section of backscattering. Figure 1 shows the distribution of nodes on the prolate spheroid and the virtual sources used in the MFS calculation. The incident preassure has been considered a plane-wave and TS has been calculated in the far-field region.

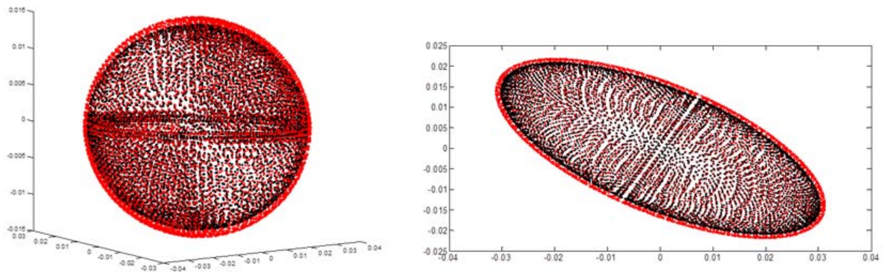

Figure 1. Nodes (black) and virtual (red) sources in MFS calculation.

The MFS has been also used in this paper to implement the backscattered field from more complex structures in near to realistic situation. In order to explore the evolution to near to far field, we have considered a simplified scheme of fish structure (Figure 2). TS has been calculated considering not only the scattering from swimbladder, but also the contribution from fish bone. To reproduce the realistic experimental situation we have modelled the emitting transducer as a flat piston and we have calculated TS evolution with distance and with relative orientation between the source and the fish. We have considered the ventral (from bottom) and dorsal (from up) insonification. The results obtained are compared with the experimental results for TS measurements of Atlantic salmon in [8].

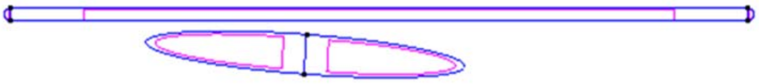

Figure 2. Scheme of fish structure. Swimbladder is approximated as a prolate spheroid and fish bone as a cylinder with smooth edges.

# 3 Results and Discussion.

We show the results for two prolate spheroids where , where is the acoustic wavenumber, given by $2\pi/c$, with f the acoustic frequency [Hz] and $c$ the sound speed [m/s], is fixed to =12 and =1 or =5.For each prolate spheroid, *nTS* has been calculated at incident angles from 0 to 50, in 2 degree steps. Sound velocity $c$ in water surrounding the prolate spheroid was 1479.6 m/s and density $\rho$=1027 kg/m$^3$. The parameters of gas inside the prolate spheroid were $c$=343 m/s and $\rho$=1.2 kg/m$^3$. The working frequency was chosen 38 kHz and the prolate spheroid dimensions were chosen to obtain the required and values. Figure 2 compares the result from MFS with the exact analytical solutions from PSMS and Kirchhoff-approximation (KA), Kirchhoff-ray-mode (KRM) and finite elements (FE) published in [5].

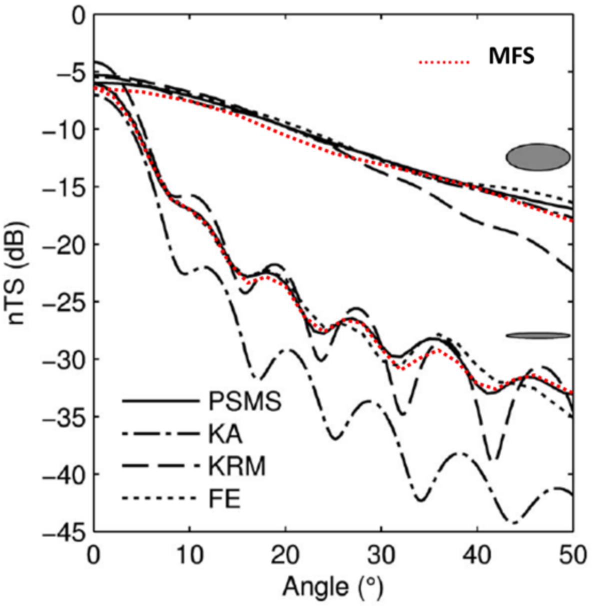

Figure 2. Comparison of MFS method scattering results with results from PSMS, KA, KRM and FE models from [5]. Results are given for two prolate spheroids with=12 and =5 (upper lines) and =13 and =1 (lower lines). Curves for PSMS, KA, KRM and FE are from Figure 4 of [5].

We underline the good agreement between the MFS results and the results obtained by exact analytical PSMS method. We have addressed the question of near-to-far field evolution of backscattered acoustic field from gas-filled prolate spheroid. Figure 3 shows how the field evolves with distance for horizontal and 30 degree tilted prolate spheroids.

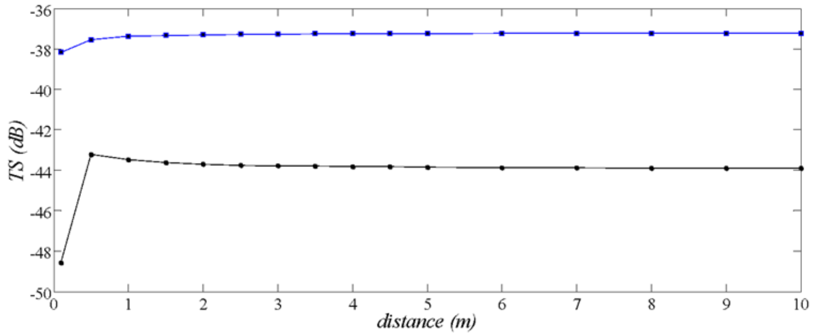

Figure 3. TS evolution with distance for a horizontal (continous) and 30 degree tilted (dashed) prolate spheroid with =3,5 cm , =1,5 and working frequency f=120 kHz. Prolate spheroid dimensions correspond approximately to the swimbladder dimensions of 20 cm length *Sparus aurata*.

The MFS has been also used to calculate TS from complex structures, as shown in Fig.2. Our purpose is to interpret some of the experimental results of TS ex-situ measurements of Atlantic salmon (*Salmo salar*) published in [8], using MFS simulations. In this calculation we have considered the following properties for the materials: $c_{bone}$ = 2273 m/s, $\rho_{\text{bone}}$=1100 kg/m$^3$, $c_{water}$= 1500 m/s, $\rho_{\text{water}}$ = 1000 kg/m$^3$ and $c_{air}$=343 m/s and $\rho_{\text{air}}$=1.2 kg/m$^3$, and only longitudinal wave propagation along the fish spine has been considered. The relation between spine and swimbladder dimensions, as well as the relative tilting angle have been chosen to approximate the internal structure of Atlantic salmon [9,10].

We offer the results corresponding to a realistic, flat piston source, working at 70 kHz with a 3.5 º beam angle at -3dB. Figure 4 shows the TS directivity of two fish with different size. We note that, because of the tilted swimbladder, the backscattering direction is not necessarily the direction corresponding to a maximum value. We analyze in Figure 5 the evolution of TS, at 50 m from the target, with the fish size. We consider both the maximum TS ($\text{TS}_{\text{max}}$) and the TS in the backscattering direction ($\text{TS}_{\text{bs}}$) (which is, in an ideal situation, the TS registered by the echosounder).

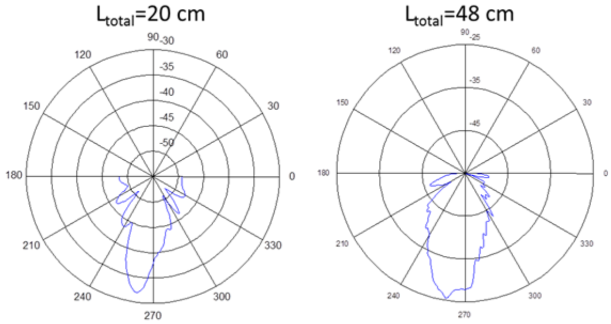

Figure 4. Directivity of swimmbladder-spine structure for salmon with total length 20 cm (left) and 48 cm (rigth). Working frequency 70 kHz, ventral insonification..

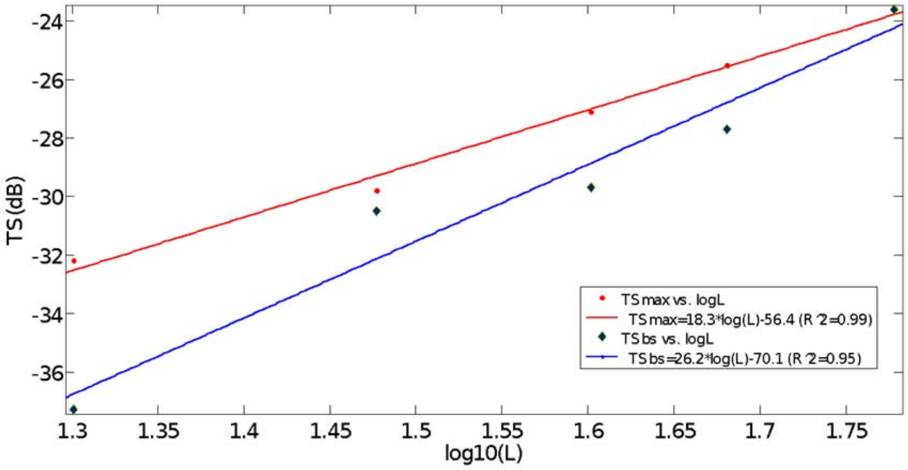

Figure 5. TS maximum (upper line) and TS in basckstattering direction (lower line) evolution with size. Ventral insonification.

We note the fair agreement with Love's expression for TS versus logarithmus of fish lenght. We can compare with the curves obtained in [8], even though the working frequency was in that case

120 kHz, the resulting curve in [8] fits with the present results. One of the main conclusions of [8] was to recommend the use of ventral insonification because of the tri-modal distributions obtained for same fish size using dorsal measurements. We have studied also differences between dorsal and ventral insonification, in order to interpret results in [8]. In Figures 6 and 7 we show the evolutions of $TS_{max}$ and $TS_{bs}$ with distance for a fish with total length 20cm for ventral and dorsal insonification, respectively.

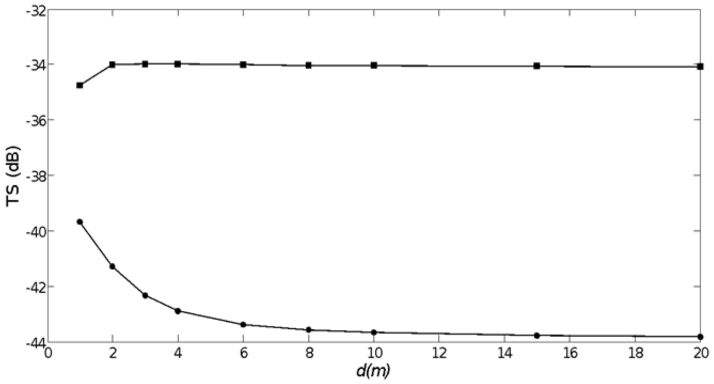

Figure 6. $TS_{max}$ (upper) and $TS_{bs}$ (lower)for 20 cm salmon versus distance, at 70 kHz, for dorsal insonification.

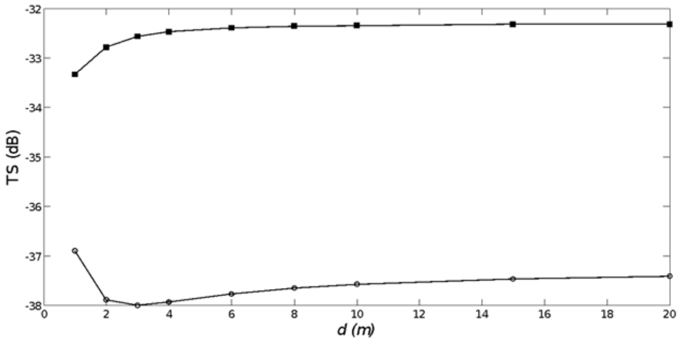

Figure 7. $TS_{max}$ (upper) and $TS_{bs}$ (lower) for 20 cm salmon versus distance, at 70 kHz, for ventral insonification.

It should be note the range between $TS_{max}$ and $TS_{sb}$ for ventral and dorsal calculations. The range of variation $\underline{\Delta}=(TS_{max}-TS_{bs})$ in ventral case is only 5-6 dB, however it is a 10 dB difference for dorsal incidence. We can represent the fish directivity at 6 m from ventral and dorsal incidence (Fig. 8).

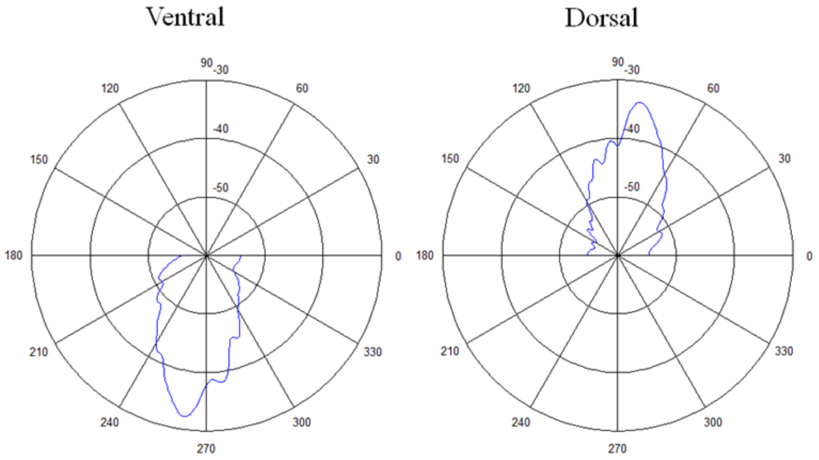

Figure 8. TS directivity at 10 m. Workig frequency 70 kHz. Fish total length 20 cm.

Tri-modal TS distribution in [8] can be interpreted in terms of the directivity and Δ range for ventral and dorsal incidence.

## 4 Conclusión

The MFS has been validated for TS calculations. The MFS results exhibit very good agreement with the exact analytical PSMS solutions for the scattering of a gas-filled prolate spheroid. The main advantage of MFS is the absence of mesh, and therefore the economy in calculation efforts. We have applied MFS to more complex structures. Considering the approximation of spine and swimbladder of Atlantic salmon we have predicted the TS dependence with fish size, orientation and distance to the transducer. Both ventral and dorsal incidences have been considered. The experimental results in [8] can been interpreted in terms of MFS results. Work in progress include to evaluate TS for higher frequencies to reproduce the exact experimental situation for all fish sizes in [8], including TS directivity for larger complex structures. Synthetical reconstruction of TS distributions considering the varibility of fish orientation and position inside the acoustical beam, in order to reproduce experimental results, should be also addressed.

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