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At-sea measurements of acoustic elastic scattering by a 1.5m-long cylinder made of composite materials

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AT-SEA MEASUREMENTS OF ACOUSTIC ELASTIC SCATTERING BY A 1.5M-LONG CYLINDER MADE OF COMPOSITE MATERIALS

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Abstract: *Monostatic and bistatic acoustic scattering measurements were performed on solid-filled fibreglass objects (a sphere and a cylinder with hemispherical endcaps) deployed proud on a sandy seabed and insonified by a rail-mounted parametric source at low frequency (roughly* ka*=5–40). The paper is limited to monostatic measurements of the cylinder. It consists of a thin-walled shell made of an approximately isotropic random-fibre material, and then filled partially with an isotropic epoxy resin and partially with sea water. The cylinder is simple enough in shape to be treated by currently available modeling techniques, but realistic enough to give a first insight into the physics of the elastic waves present in such material combinations. Preliminary data analysis indicates that the scattering signatures are dominated by the solid filling. The experimental data were acquired in October 2006 during the EVA-06 trial off the Island of Elba.*

Keywords: *low-frequency target scattering, parametric sonar, data analysis*

1. INTRODUCTION

The main objective of the EVA-06 sea trial was twofold: recording low-frequency, broadband (roughly 2–18 kHz), scattering data from targets of different shape and materials, and measuring the reverberation of different kinds of seabed in the frequency band 4–50 kHz. This paper is limited to the former part of the experiment. A 1.5m-long, solid-filled, cylindrical shell was deployed proud on a sandy seabed in the coastal waters of Elba Island (Italy), and insonified by a parametric source at low frequency. The cylinder consists of a thin-walled, fibreglass shell made of an approximately isotropic random-fibre material, and filled partially with an approximately isotropic epoxy resin and partially with sea water. Its response to multiple aspect insonification was collected in both monostatic and bistatic configurations, both in the near field and in the far field of the object itself. The paper is limited to monostatic, far-field measurements. In past sea trials [1-3] the scattering response was measured from proud and buried empty steel spherical shells and flat-endcapped, water-filled, steel cylinders in the same bandwidth. The materials and structure of the previous targets made their scattering response much easier to interpret. A selection of data is presented and compared to simulations obtained by the AXISCAT modelling tool [4]. Elastic wave analysis is applied to interpret the data structure. Preliminary to EVA-06, tank measurements [5] were performed roughly in the same *ka* range on small spheres made of approximately the same materials. Those measurements allowed the estimation by acoustic inversion of the elastic properties of the materials, with which to feed the AXISCAT model.

2. DESCRIPTION OF THE EXPERIMENT AND DATA PRE-PROCESSING

Monostatic, multiple-aspect target scattering measurements were performed by using an endfire parametric source mounted on a 24m-long rail (Fig. 1(a)), and a linear array of 16 elements and an aperture of 1.41 m, mounted vertically in a quasi-monostatic configuration. The source could rotate in pan and tilt with a precision of about 1^o. At low frequency the source has a -3dB beamwidth of 8^o (horizontally) by 4^o (vertically) at 8 kHz, and a -3dB bandwidth roughly between 4 and 14 kHz. Its non-linear interaction region is estimated to extend to the first 11 m in front of the transducer. Details on the sonar system characteristics can be found in [1]. The sonar was mounted on a telescopic tower, with height varying from 6 to 10 m. Hence it allowed the measurement of the target field at different grazing angles. The seabed was of compact, fine sand. The water depth was between 12 and 14 m in the area, having a slope up (of about $3\text{-}4^o$) from the rail towards the target field. Isospeed conditions were measured in the water column at 1530 m/s.

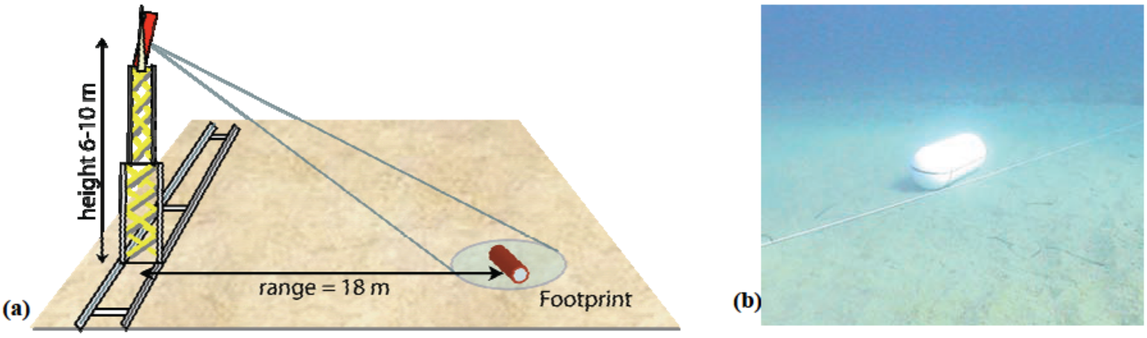

Fig.1: (a) Experiment geometry (not to scale). 3D view. (b) Cylinder on the seabed.

A cylinder (Fig. 1(b)) was deployed proud on the seabed in front of the rail, 18 m from the rail itself. It is a hemispherically endcapped cylindrical fibreglass shell of 1.5m length, 0.5m diameter and 1cm thick walls, filled with an epoxy resin for the 5/6 of its length, leaving one hemisphere filled with sea water. From acoustic inversion applied to scaled spheres of the same materials measured in a tank [5], and from further model tuning on the EVA target the estimated fibreglass properties were: density ρ=1845 kg/m^3, compressional speed c_p=3000 m/s, shear speed c_s=1550m/s with respective attenuations

0.35 and 0.85 dB/λ. The estimated filler parameters were: ρ=1845 kg/m^3, c_p=3060 m/s, c_s=1580 m/s with attenuations 0.5 and 0.8 dB/λ respectively.

The data selected are the aligned coherent averages over 60 pings of the beamformed acquisitions by the vertical array, bandpassed between 2.5 and 18 kHz. The incident pulse was a Ricker pulse [1] nominally centred at 8 kHz. Figure 2 shows the spectrogram of two data samples. A complicated echo structure follows the front echo in both cases.

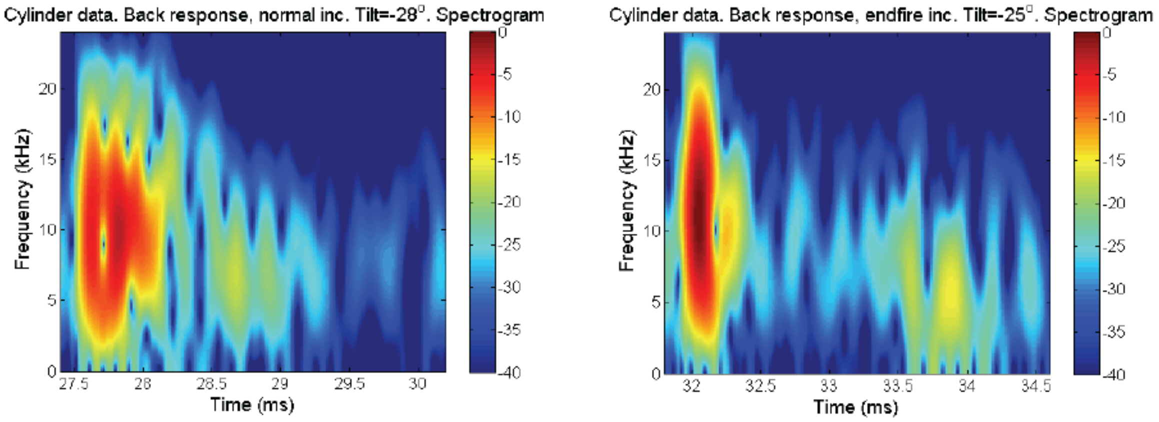

Fig.2: Beamformed data samples of backscattering from the cylinder at normal (left) and endfire (right) incidence. Response to a Ricker pulse nominally centred at 8 kHz. The spectrograms (in dB) are shown normalized to the maximum of the two images.

3. THE *AXISCAT* MODELING TOOL

AXISCAT [4] is a frequency-domain Finite Element (FE) model for computing the radiation and scattering from axially-symmetric fluid-loaded structures subject to a non-symmetric forcing field. Using an azimuthal Fourier series expansion of the 3D acoustic and elastic fields, the 3D FE problem is separated into a series of independent smaller 2D problems. The Bérenger PML [4] is used to emulate the Sommerfeld radiation condition for free-field targets as well as for targets inside layered fluid media. For those cases where an axisymmetric structure interacts with a water-sediment interface, if the overall symmetry is broken but the target is still axisymmetric, such as in the proud cylinder case, the single-scattering approximation is obtained by computing the scattered field components for the target in the free field, generated by the directly-incident field and by the bottom-reflected incident field, respectively. The far-field scattered pressure is computed from the FE solution sampled on the target surface via the Helmholtz-Kirchhoff integral, by employing the appropriate Green's functions for the free field or for the layered medium.

4. MODEL-DATA COMPARISON: RESULTS AND DISCUSSION

Model-data comparison is limited here to the composite cylinder insonified at normal incidence and on the water-filled endcap (Fig. 3). The results are shown in Figs. 4 and 5 respectively. Figure 6 shows the physical interpretation of the echo structure in terms of main diffractive and elastic effects. The object model was meshed with Lagrange cubic elements, the size of which was selected according to the convergence criterion in [4].

This lead to the following element distribution: 50 elements along half of the cylindrical body, 20 elements along half of each hemisphere, 16 across the PML, 1 across the thickness, 18 along the cylinder inner radius. The parameters of the materials are listed in Section 2. For the sediment a sound speed of 1650 m/s was used in the band 3-18 kHz (corresponding to a nominal critical angle of 22^o); the density was set to 1900 kg/m^3 [1]. The model assumes plane wave incident field, which is only roughly true at the object slant range (being 21 m at normal incidence, and 24 m at endfire, with the sonar far-field limit estimated at 30-35 m). The grazing angle was tuned to optimize model-data fitting.

At normal incidence (Fig. 4) the interference between direct and bottom-bounce returns is shown to play a major role as the bottom-reflected front echo is strong and partially overlaps the elastic scattering components of the time response. The spectrum is dominated in the whole bandwidth by this interference (Lloyd-mirror effect), which is extremely sensitive to geometrical parameters such as grazing angle and sediment properties, all known with insufficient accuracy. Consequently, the model-data comparison is less accurate in the frequency than in the time domain. The comparison of the time series is extremely accurate until t=28.3 ms, which implies that the estimated material properties are correct. Amplitude and phase discrepancies occur around 28.45 and 28.8 ms, at the arrival of echoes of the Scholte-Stoneley wave travelling at the filler-shell interface (Fig. 6 (a)). The tank data analysis [5] showed that this discrepancy is due to the selection of perfect-bonded boundary condition between the filler and the shell: an intermediate condition between pure transverse slip and perfect contact should be more realistic. A disagreement of the same nature can be noticed in the endfire data at 33.2 ms (echo of the axial Scholte-Stoneley wave). A model refinement is under investigation.

When the sonar points to the cylinder's water-filled endcap (Fig. 5), the model-data comparison is generally good in the time domain. The main discrepancy is on the small echo around 32.3 ms, which is due to diffraction effects, hence is linked to a non-perfect knowledge of the geometry or of the seabed properties. The comparison of the spectra is very good in the band 3-8 kHz. The low-frequency equally-spaced dips come from the sound propagating and bouncing inside the filler at its shear speed (see Fig. 3 (a)), and arriving at 33.8 ms. Between 8 and 13 kHz the dips are related to the same kind of wave, but propagating at the filler compressional speed: its phase and amplitude do not perfectly fit, as confirmed by its time echo at 33.6 ms. Depending on the geometry, the path of some of these internal bounces may interact with the bottom (see the example in Fig. 3(b)). Hence the non-precise knowledge of the geometry and of the sediment properties may have caused the disagreement noticed at 33.6 ms. Another possible reason may be the presence of local inhomogeneities (e.g., air bubbles) in the filler. At higher frequencies the measured elastic response is very weak and comparable to the reverberation/noise level.

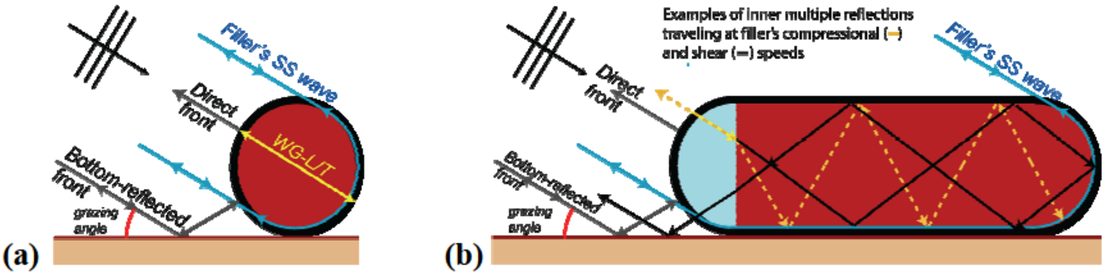

Fig.3: Direct and bottom-reflected sound to and from the cylinder at (a) normal and (b) endfire incidence. The supported wave travel paths are sketched coming from direct insonifications. An analogous set of waves is generated by the bottom-reflected sound.

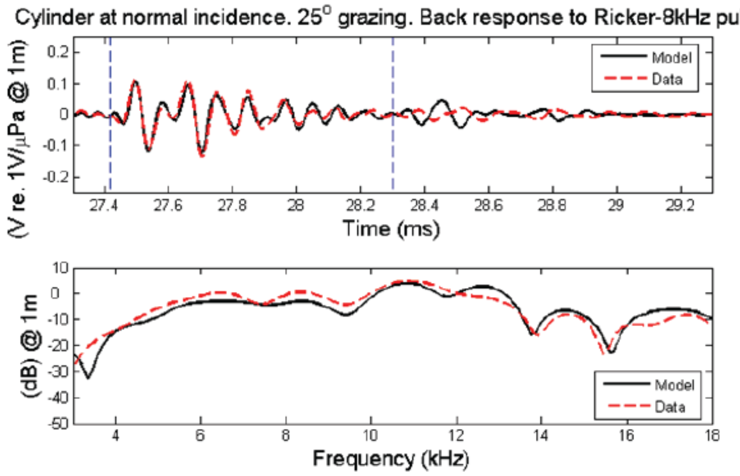

Fig.4: Cylinder at normal incidence. Model-data comparison in time and frequency domains. Spectra are computed from the data segments within the blue dashed lines.

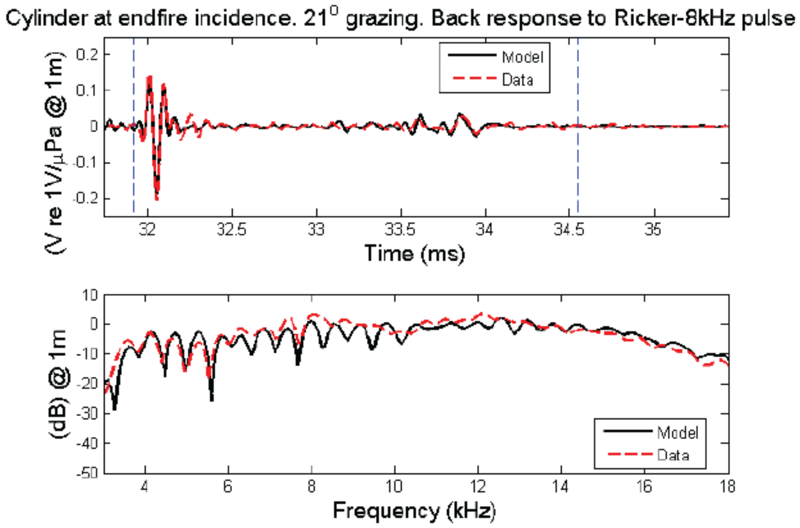

Fig.5: Cylinder at endfire incidence. Model-data comparison in time and frequency domains. Spectra are computed from the data segments within the blue dashed lines.

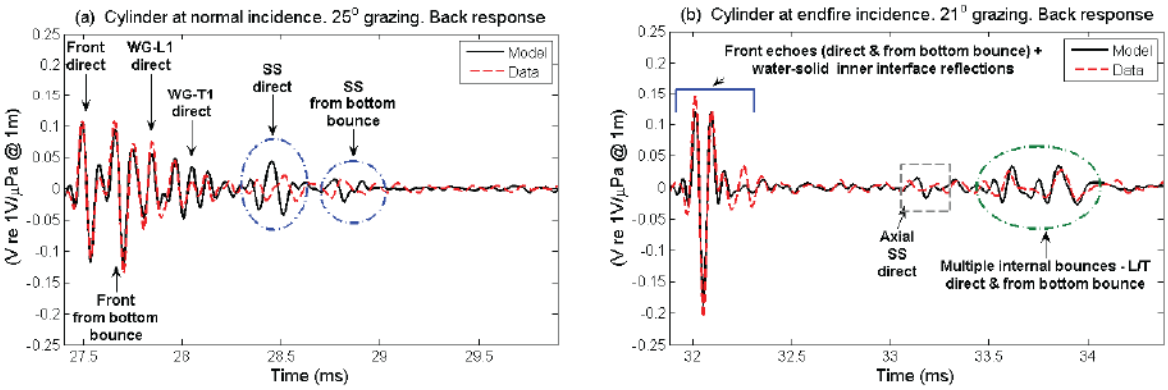

Fig.6: Wave analysis applied to the time responses of the cylinder at normal (a) and endfire (b) incidence. Only the strongest echoes are considered. WG stays for Whispering-Gallery, SS Scholte-Stoneley, L longitudinal, T transversal wave.

5. CONCLUSIONS AND FUTURE ACTIVITIES

The paper presents a selection of scattering data acquired during the EVA-06 sea trials under relatively controlled and repeatable geometry. Results of model-data comparison and wave analysis are shown that aim at the validation of the target scattering modelling tool AXISCAT. The successful model-data comparison shows that the model is generally capable to properly and accurately describe the physics. This activity will continue with the monostatic measurements of the cylinder at different grazing angle, at different aspects, as well as with near-field bistatic data and with data from a half-filled sphere made of the same materials.

The inspection of the real data shows how elastic wave effects are supported also by resin-filled fibreglass objects having relatively complex internal structure. The levels of the excited wave echoes are high enough to be detectable even in the presence of interference with the seabed. The elastic response is dominated by waves supported by the filler, while the shell appears to be almost acoustically transparent.

Due to the broadband insonification, the destructive interference with the seabed, localized at certain frequencies depending on the grazing angle, has limited effect on the overall echo structure. This effect will be analyzed also at other grazing angles, including subcritical.

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