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MEASUREMENTS OF ACOUSTIC SCATTERING FROM PARTIALLY AND COMPLETELY BURIED SPHERICAL SHELLS

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Jan L. Spoelstra
Director

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Executive Summary: Mines which are completely buried in sandy ocean sediments are generally considered to be unclassifiable by conventional high frequency minehunting sonars due mainly to the low levels of energy transmitted into the sediment at these frequencies at the low grazing angles used for minehunting. As penetration is increased at lower frequencies, the possibility of using lower frequency sonars (around 10 kHz) with wider fractional bandwidth (2-20 kHz) has been investigated. At these frequencies sound should penetrate better into the sediment and into the targets, if elastic.
The main contributions to target echo are the specular reflection and potential diffraction effects (from the external shape of any object, also at high frequencies) and the *resonance* response in the case of man-made elastic objects possessing particular symmetries (e.g., bodies of revolution). The resonance response derives from elastic periodic phenomena such as surface circumferential waves revolving around the target.

The methodology of low-frequency target classification is based on the time and frequency analysis of all the target echo contributions in order to extract information on external shape and size (from diffraction analysis) and geometrical and elastic parameters (e.g., shell material and thickness, inner medium properties) from resonance analysis. The potential of this methodology was successfully demonstrated on simulated and real data (by exercise mine, cylinders, spheres and rocks) from targets suspended in free space or proud on the seabed.

The main goal is to verify from models and measurements at sea whether the resonance contribution measured by an elastic axisymmetric target in free space is still detectable and identifiable when the target is buried. Analysis aims to evaluate how the elastic wave dynamics changes with burial depth. The targets selected are air-filled spheres, characterized by few families of resonance waves in free space, which have been measured in free field, as well as half-buried and flush buried in a sandy bottom.

From the data, the existence and evidence of the expected elastic waves is shown for the buried targets. The amplitude levels of the resonance component are comparable, relative to the specular echo, with those observed in the free-field. This positive result demonstrates the applicability of low-frequency methodologies based on resonance analysis to the classification of buried objects.

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Measurements of acoustic scattering from partially and completely buried spherical shells

A. Tesei, A. Maguer, W.J.L. Fox,
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Abstract: Recent work at NATO SACLANT Undersea Research Centre has concentrated on investigating the use of low frequency sonars (2-20 kHz) in order to better exploit scattering features of buried targets that can contribute to their detection and classification.

Part of the recent GOATS'98 experiment performed off the island of Elba, involved controlled monostatic measurements of scattering by spherical shells which were partially and completely buried in sand, as well as suspended in the water column. Analysis is mainly addressed to a study of the effect of burial on the dynamics of backscattered wave families, which can be clearly identified in the target responses. Data interpretation results are in good agreement with theory.

Keywords: sound scattering ∘ buried objects ∘ elastic wave dynamics ∘ resonance analysis

Contents

1
Introduction

Acoustic scattering by man-made elastic objects, partially or completely buried in sea bottom sediments, is studied by resonance analysis of data from spheres deployed at various burial depths.

From the analysis of wave scattering by underwater elastic objects at low intermediate frequencies (ka $\in$ (2,40)), several features can be selected which are related to object elastic parameters (e.g., radius, wall thickness, material) and hence, can be used for identification purposes [1][2]. The frequency range selected (f$\in$(2,20) kHz) should allow both a better penetration into sediments and into elastic targets. The main goal of this work is to verify from scattering measurements at sea whether the circumferential waves backscattered by an elastic axisymmetric target in the free space remain sufficiently detectable and identifiable when the target is buried. Further, analysis aims to evaluate how the burial depth, the outer sediment and the presence of the seabed interface influence the generated wave dynamics.

The target selected is an air-filled sphere of intermediate thickness (i.e., h$\approx$ 0.056, being h the ratio between wall thickness and outer radius), the backscattered response of which in the free space has been accurately modeled and interpreted [3][4], and is relatively simple, being characterized by few wave families.

Comparison of theoretical models and experimental data [5][6] shows the existence and evidence of resonance waves, and evaluates the change in the response with burial depth, sediment type and grazing angle. Recent work (e.g., [6][7]) presents models for partially buried spheres or cylinders, and studies response dynamics as a function of burial depth and grazing angle.

This paper describes the analysis of wave backscattering measured from two identical spheres deployed half- and flush-buried in a sandy bottom. The analyzed data were acquired in the context of GOATS'98 experiment [8].

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Experimental setup

The GOATS'98 experiment was carried out in May, 1998, on a sandy bottom in 12-15 m water near Marciana Marina, off the island of Elba. The parametric sonar used, the SACLANTCEN SIMRAD TOPAS, generates a highly directional beam in the secondary frequencies between 2–16 kHz.

The experimental configuration is shown in Fig. 1. In order to acquire data from various source-receiver geometries, the transmitter was mounted on a 10 m tower. The tower in turn was mounted on a 24 m linear rail on the bottom, along which its position could be precisely controlled. The TOPAS transmitter was mounted in a Pan-and-Tilt assembly so that the transmission direction could be accurately measured. A 16-element linear receiving array was mounted vertically in a near-monostatic geometry. Three identical spheres were deployed in line with the TOPAS rail at different burial depths (50 cm into the sediment, flush and half-buried). The half-buried sphere was also measured before burial (under quasi-free-field conditions in the water column). The flush- and half-buried spheres and the free-space measurements are all evaluated in this paper. The spheres were air-filled, steel shells of 1.06 m diameter and 3 cm wall thickness.

Isospeed conditions were measured in the water column at 1520 m/s. The depth of the water over the target field was $\approx$ 12 m. Grain size estimates of the bottom corresponded to medium sand, with an average density of 1.91 g/cm^3. Sound speed was estimated to be on the order of 1720 m/s by pulsed travel time measurements on sediment cores centred at 200 kHz. Hence the sand critical angle is estimated at 28^o.

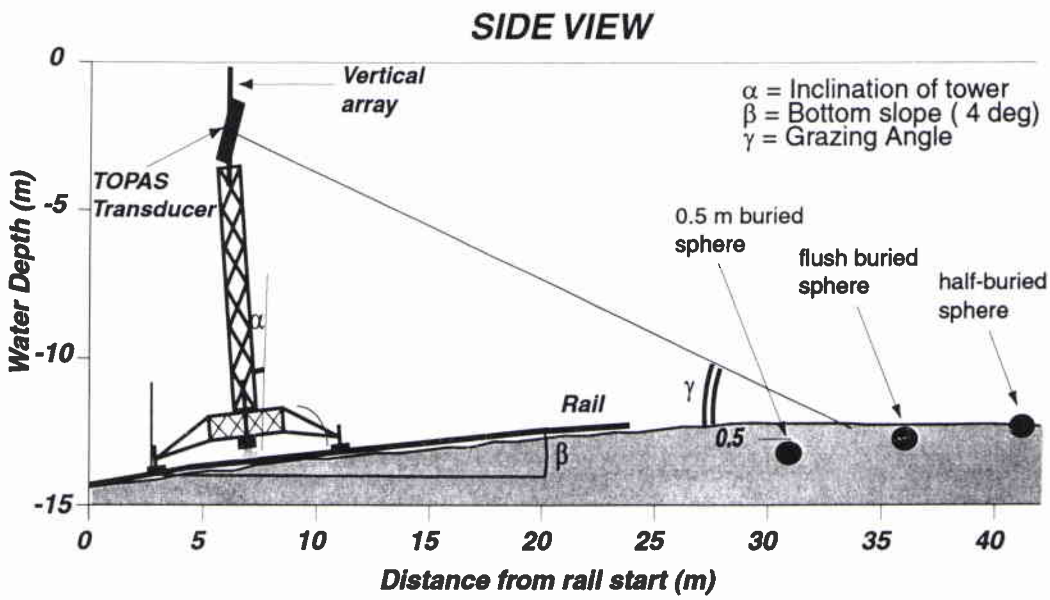

Figure 1 *Experimental configuration.*

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Basic scattering concepts (free space)

Figure 2 shows the simulated response of a water-loaded canonical sphere to a Ricker pulse with central frequency around 8 kHz, corresponding to $ka \approx 18$. The modeled and measured spheres have the same nominal elastic parameters, and the sea water speed is set to 1520 m/s. Wave scattering is analyzed in terms of wave speed dispersion curves. The phase and group speeds of the n^{th} modal frequency f_n of a wave, traveling along a path of radius R, are defined [9][10] as:

$$\begin{aligned} |c_{ph,n}| &= \tfrac{2\pi R f_n}{n+1/2} \\ c_{g,n} &= 2\pi R(f_n - f_{(n-1)}). \end{aligned} \tag{1}$$

In the selected frequency range, two wave families are outlined as the most significant. The shell-borne supersonic symmetric S_0 Lamb-type wave which travels with phase and group speeds asymptotically tending to the shell material membrane speed, c^*. The outer-fluid-borne subsonic A_{0-} antisymmetric Lamb-type (creeping) wave which has the phase speed tending to the outer medium sound speed and the group speed reaching its maximum at the coincidence frequency, f_c, i.e., the frequency at which this family is coupled in phase with the A_{0+} antisymmetric Lamb-type wave. In this frequency range the the A_{0+} wave, which is shell-borne and follows the same path as the S_0 wave family, is not detectable as its backscattered component damps very quickly once reradiated out of the shell wall.

The travel path radius R for the shell-borne S_0 wave approximately corresponds to the average between the sphere outer and inner radii, a and b respectively:

$$R_{S_0} = \frac{a+b}{2}. \tag{2}$$

For the outer-fluid-borne wave A_{0-}, R coincides with the sphere outer radius, a:

$$R_{A_{0-}} = a. \tag{3}$$

The simplified scheme in Fig. 3 shows the travel paths followed by the Lamb-type waves revolving around the spherical shell.

A simple empirical formula, which was shown [11] to be valid for steel, aluminum and similar materials, allows the approximate estimation of the average outer-medium

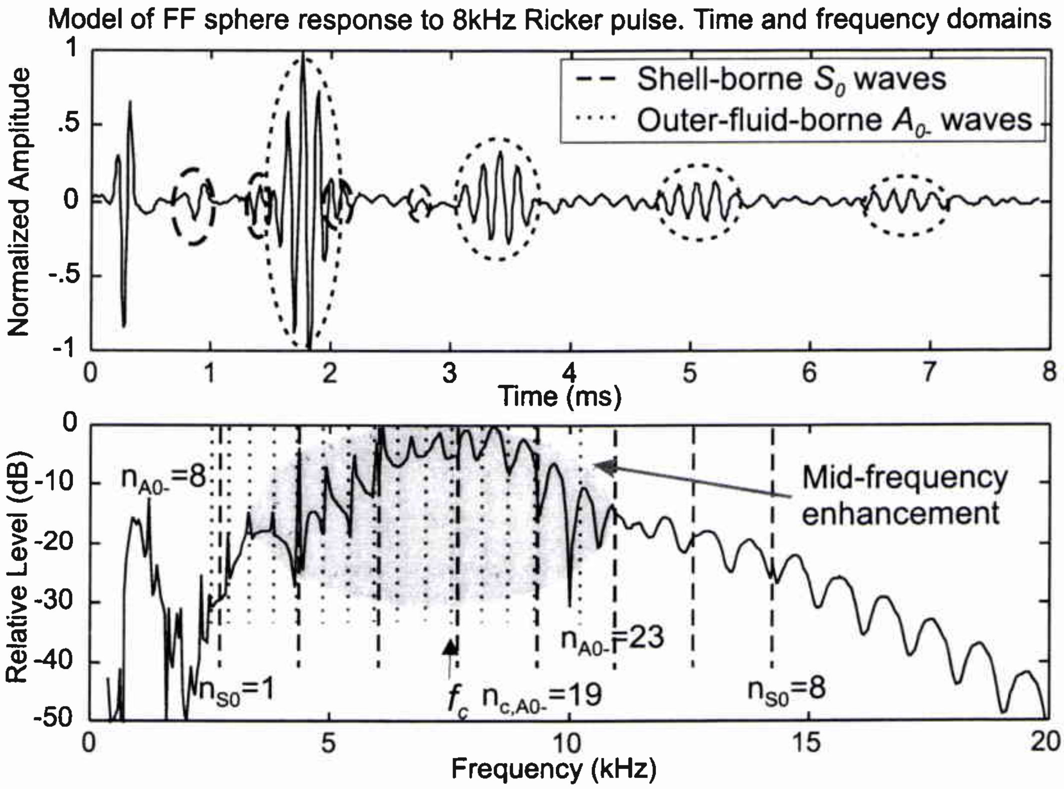

Figure 2 *Model of free-field sphere backscattering.*

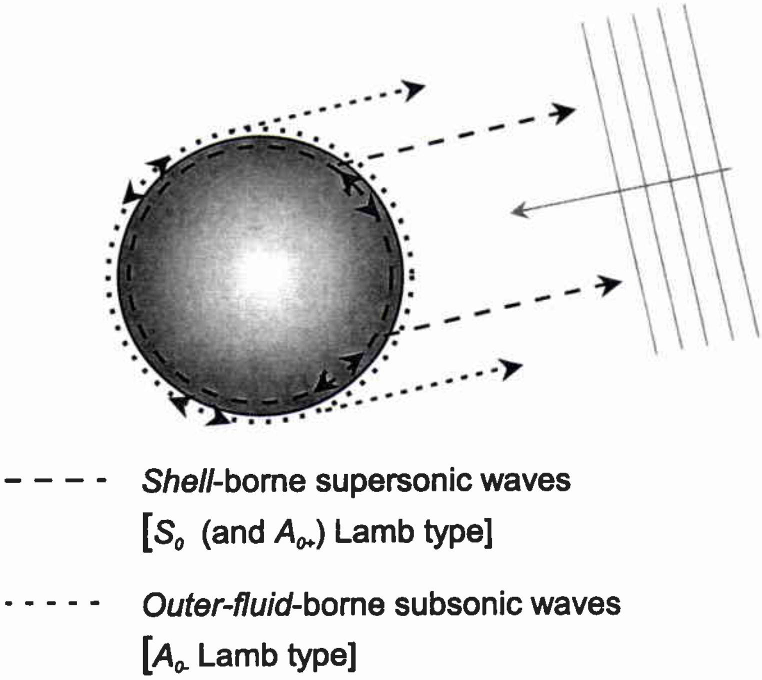

Figure 3 *Simplified scheme of travel paths of the main elastic waves backscattered by an air-filled sphere at low-intermediate frequencies.*

sound speed from f_c and the shell wall thickness d:

$$c_{out} \approx f_c 2\pi d. \tag{4}$$

The phase and group speeds computed from the identified wave modes (labelled n) are plotted in Fig. 4.

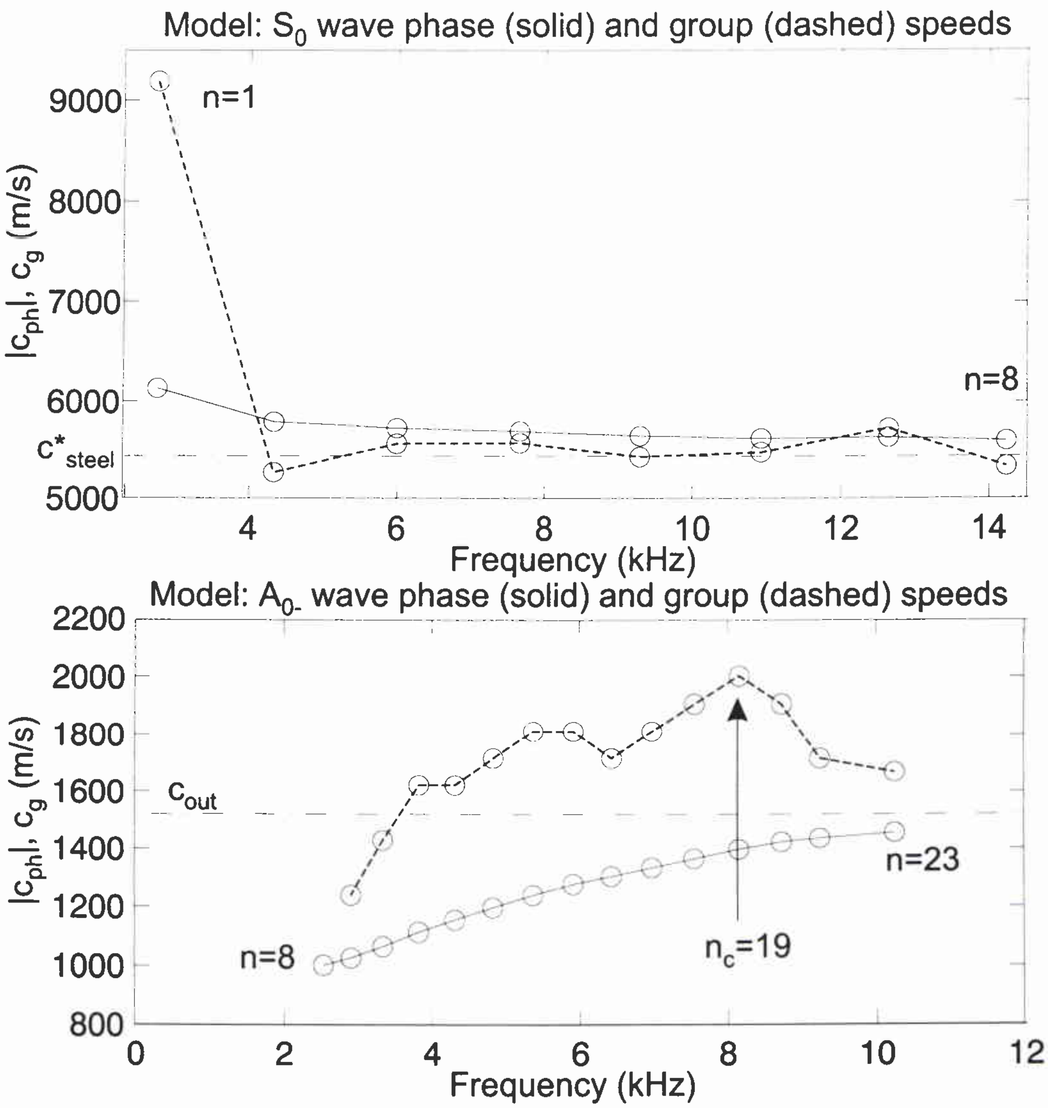

Figure 4 *Lamb-type waves dispersion curves (model).*

4

Experimental results

The data selected are the aligned average on 50 pings of the beamformed acquisitions by the vertical array. For buried cases, the grazing angle was low in order to limit reverberation, but above the sediment critical angle in order to increase penetration.

4.1 *Free field sphere (FF)*

The response of the sphere suspended in mid-water is presented in Fig. 5, where comparison with the computed model is outlined. Model-data agreement is good in feature identification, but poor in level prediction, at late time, due to imperfections in sphere. Indeed, a decay of about 5 dB of the measured mid-frequency enhancement is estimated with respect to expectation. This mismatching is evident also in the time domain in correspondence with the A_{0-} wave echoes. It may derive from potential non-uniformity of the sphere wall thickness and/or from the presence of a steel ring attached to the top of the sphere.

In Fig. 6 the wave scattering interpretation is shown. Wave dynamics, which is in good agreement with theory, appears to be uninfluenced by sphere imperfections.

The details of the extraction and fitting of the resonances to the spectrum are given in reports [1][12].

4.2 *Flush-buried sphere (FB)*

The response of the flush-buried sphere is plotted in Fig. 7. The grazing angle is 35^o, i.e., above the sand critical angle. As shown in Fig. 8, both the wave families outlined in free-field data are evident and their scattering levels relative to the specular echo are comparable with the FF case. Wave mode localization derives from comparison to free-field data and to the best-fitted free-field model, obtained for c_{out}=1642 m/s, compared to data in Fig. 7.

From $\hat{f}_c$ localization, obtained by picking either the peak of the spectrum in correspondence of the mid-frequency enhancement or the maximum of the A_{0-} wave

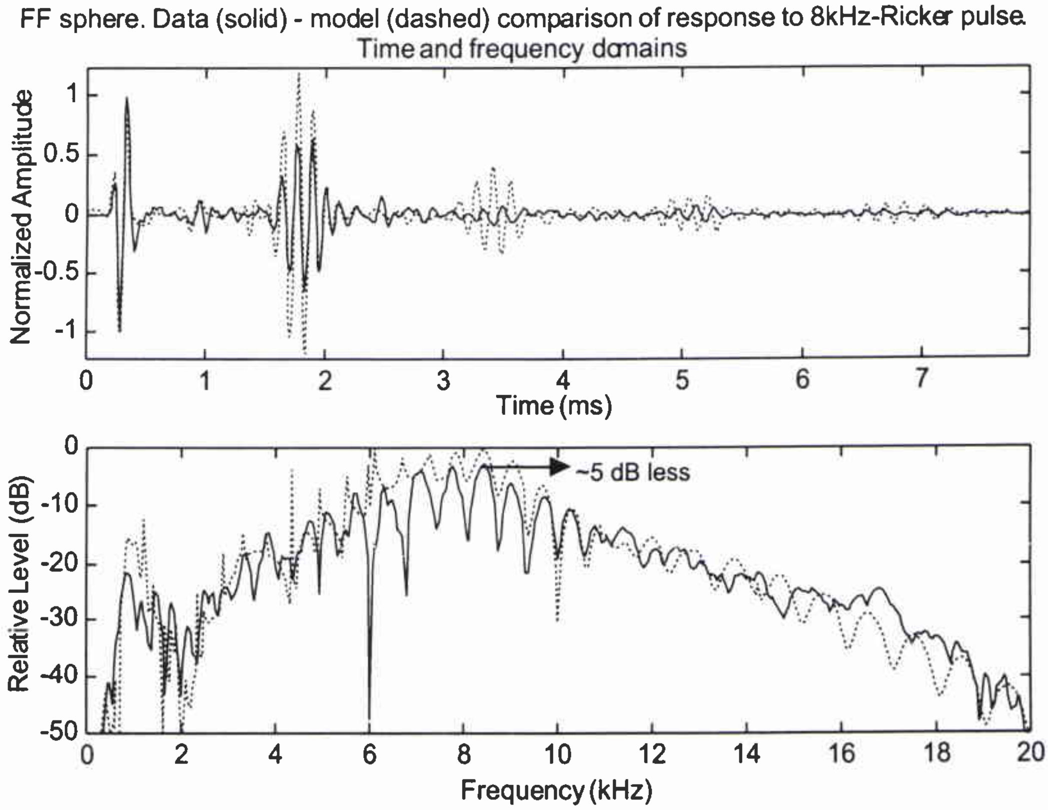

Figure 5 *FF sphere. Model-data comparison.*

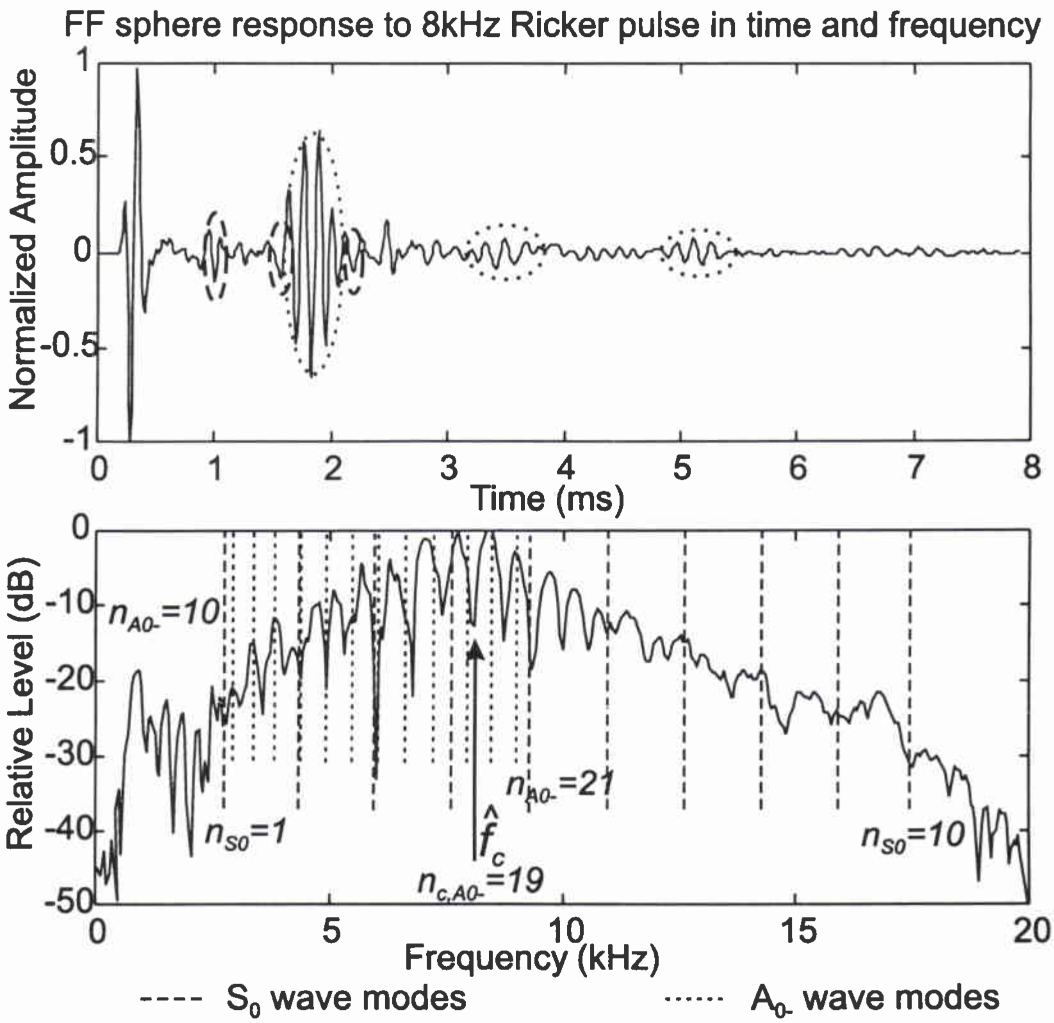

Figure 6 *FF sphere. Wave scattering analysis. The S_0 and A_{0-} wave modes are extracted as explained in [1][12], and are identified on the basis of model-data comparison. $\hat{f}_c$ is localized by picking the peak of the envelope of the spectral mid-frequency enhancement.*

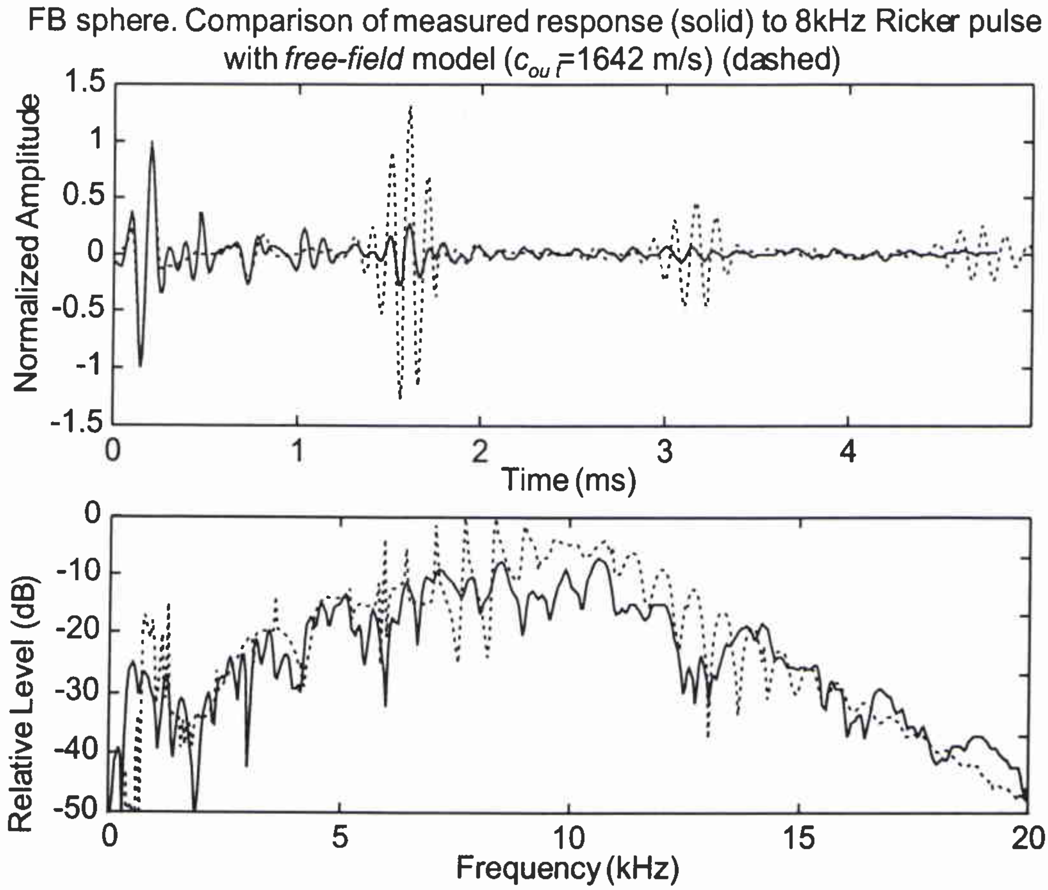

Figure 7 *FB sphere. Model-data fitting.*

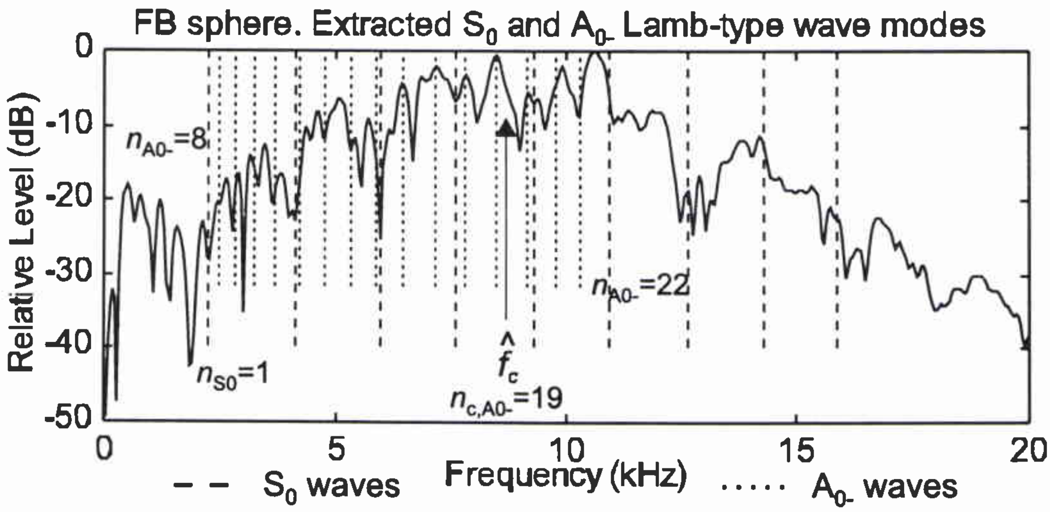

Figure 8 *FB sphere. Wave modes identification.*

group speed curve [1], Eq. (4) provides the outer medium speed estimate of 1652 m/s. Both these values differ significantly from the measurement (1720 m/s) obtained at 200 kHz, in agreement with theoretical predictions for which the speed of the porous media reduces as frequency is reduced, as measured and discussed in [13]. These considerations influence also the estimation of the sediment critical angle which should decrease as the frequency is reduced.

4.3 Half-buried sphere (HB)

The HB sphere response is compared with the best-fitted free-field model in Fig. 9. The grazing angle is about 26^o, compared to the critical angle of 28^o (as estimated from the sediment speed measurements at 200 kHz). This case is the most complicated to interpret, due to the potential presence of multipath [12], as confirmed by the evident effects of phase reverse between data and the free-field model. However, both the wave families are still identified (Fig. 10) and have relative levels comparable with the FF and FB cases.

From $\hat{f}_c$ localization, the outer medium speed estimate is 1555 m/s (the value for the best-fitted model is 1565 m/s), which can be assumed as a weighted average between the sound speeds in water and in sediment, i.e., the two media in which the A_{0-} wave travels. Under this interpretation, the A_{0-} wave is not reflected by the seabed interface.

4.4 Compared analysis

The dispersion curves of the S_0 and A_{0-} waves estimated in the FF, HB and FB cases are compared in Figs 11 and 12 respectively. The behavior as burial depth changes is predictable using simple theoretical arguments.

The first 3 modes (but particularly the first one) of the S_0 wave shift down in frequencies with burial depth, which is a predictable [7] inertial loading phenomenon. For higher frequencies, the expected higher dispersion due to the sediment is negligible, all the three curves almost coincide and tend to c^*_{steel}, as expected.

In accordance with theory, the phase and group speeds of the A_{0-} waves tend to increase with burial depth (i.e., with the average speed of the outer media in which this wave travels) and frequency. The whole mid-frequency enhancement region shifts up with burial, together with the coincidence frequency, which is linearly related to the average outer-medium sound speed according to the empirical formula of Eq. (4).

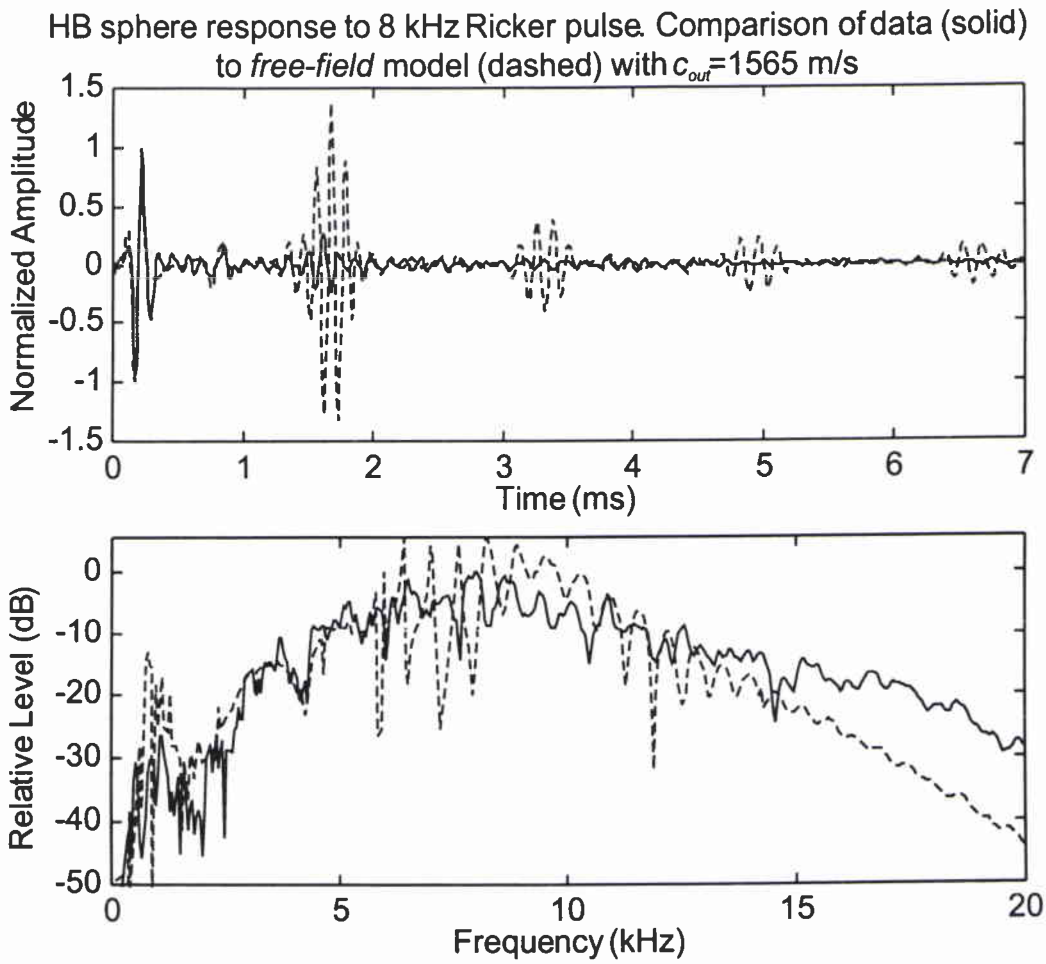

Figure 9 *HB sphere. Model-data fitting.*

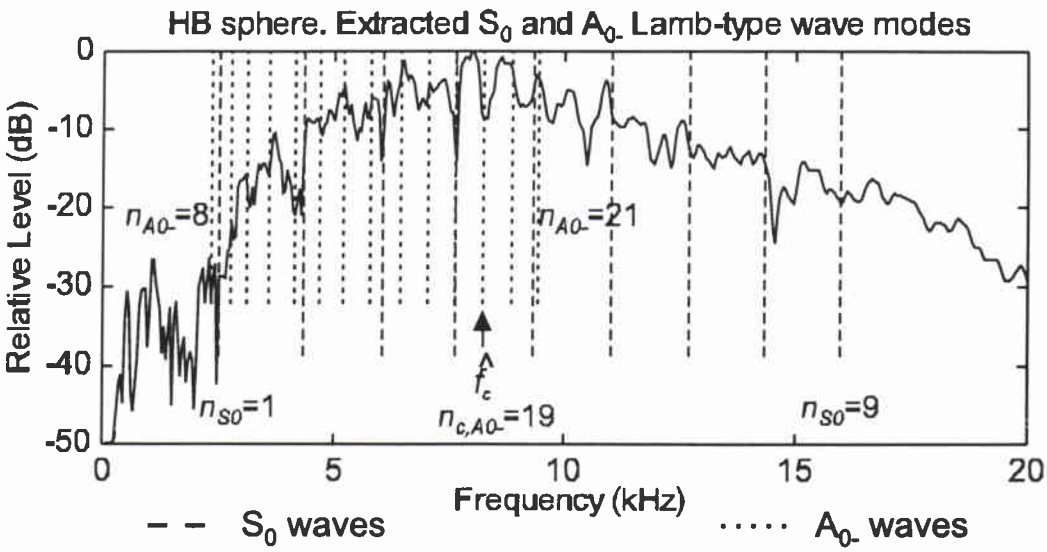

Figure 10 *HB sphere. Wave mode identification.*

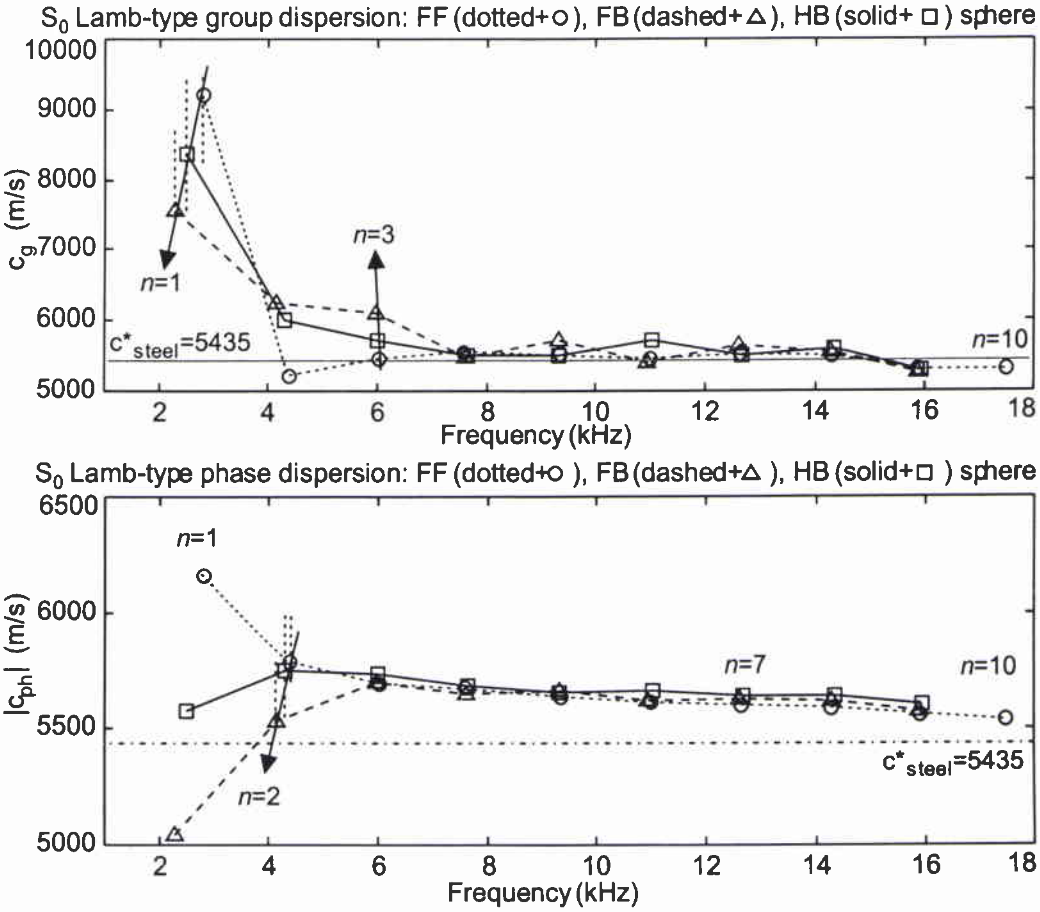

Figure 11 *Comparison of S_0 wave dispersion curves.*

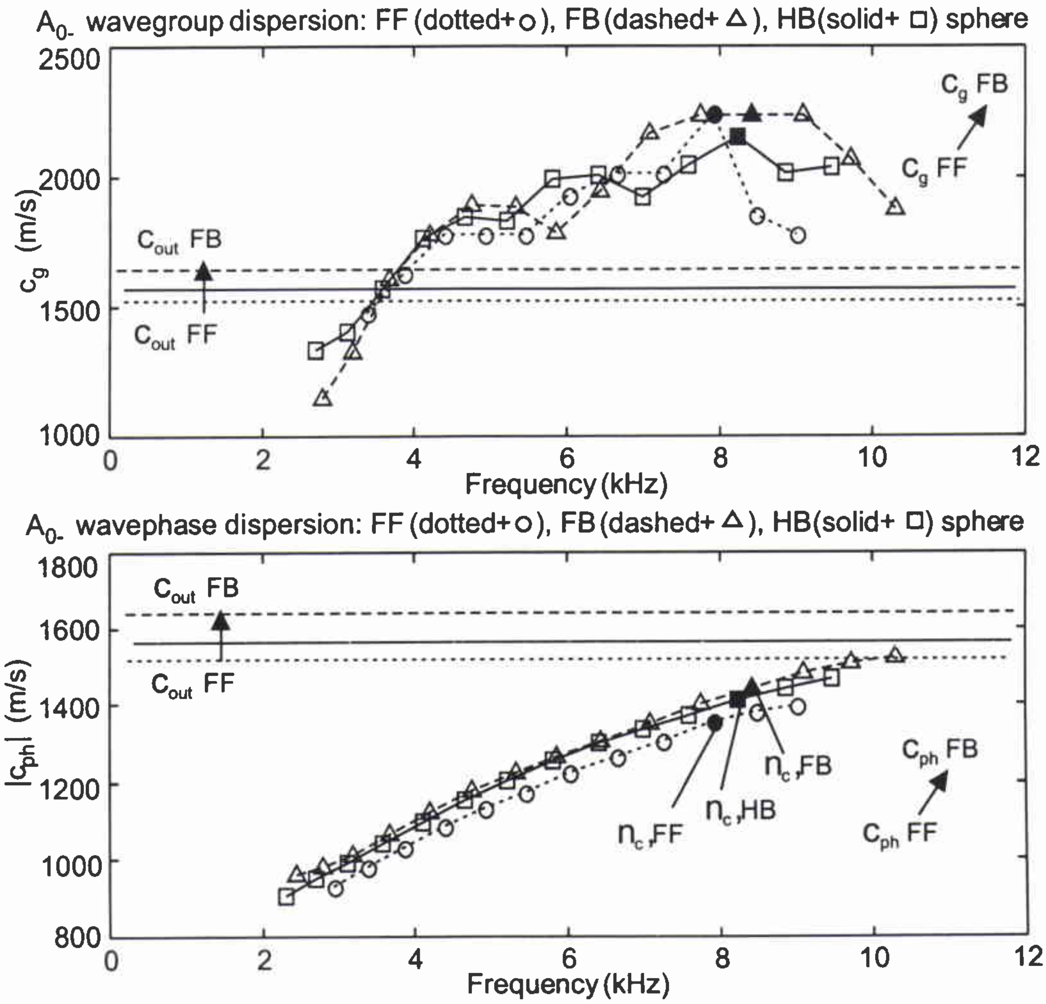

Figure 12 *Comparison of A_{0-} wave dispersion curves.*

5 Conclusions

The dynamics of elastic wave scattering measured from spheres buried in the seabed have been studied as a function of burial depth. The free field measurements of one of the spheres are used as a reference case.

In the model-data comparison applied to the free-field sphere, a very good fit is found in terms of dispersion curves of the symmetric and subsonic antisymmetric Lamb-type wave families, but a significant disagreement in mid-frequency enhancement level is outlined, potentially caused by sphere imperfections and/or attached external structures (e.g., a steel ring on the top of the sphere).

The interpretation of half- and flush-buried sphere responses showed sufficient agreement with theory [5] regarding the dynamics of symmetric and subsonic antisymmetric Lamb-type wave families, i.e., the same two families of elastic waves expected and identified in the free-field case. These waves can still be identified in both burial conditions, with levels, relative to the specular echo, comparable to the free-field case. Among the future activities, the comparison with more realistic simulators of scattering by partially and completely buried spheres will be considered. Further, the analysis of elastic wave dynamics will be applied on simulated and real data as the grazing angle varies above the critical angle, at several fixed burial depths.

Finally, the sound speed in sand at 8 kHz through mid-frequency analysis has been found to be much lower than the value measured at 200 kHz, which is in agreement with the results obtained in [13] and with theory of sound propagation in porous media. This effect can be more directly confirmed by using more realistic scattering models and by conducting further data analysis.

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