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TANK MEASUREMENTS OF ELASTIC SCATTERING BY A RESIN-FILLED FIBREGLASS SPHERICAL SHELL

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Abstract: *Acoustic elastic scattering measurements were conducted in a tank on a 6cm-radius fibreglass spherical shell filled with a low-shear-speed epoxy resin. Preliminary measurements were conducted also on the void shell before filling and on a solid sphere of the same material of the filler, in order to estimate the constituent material parameters via acoustic inversion. The objects were measured in the backscatter direction, suspended at mid water, and insonified by a broadband directional transducer. From the inspection of the response of the solid-filled shell it was possible to detect and characterize inhomogeneities of the interior (air inter-layers), the presence of which were later confirmed by CT scan and ultrasound measurements. Elastic wave analysis and analytical modeling tools supported the physical interpretation of the measured responses.*

Keywords: *Tank experiments, non destructive testing, elastic scattering analysis*

1. INTRODUCTION

Low-to-mid frequency sound has been experimentally shown to penetrate into the metallic casing of an elastic object, and hence provide information on its interior structure and content. The aim of this study is to investigate if low-frequency elastic scattering can be significant (with respect to diffraction) also in the case of composite objects made with dissipative low-shear-speed materials, i.e., plastic-like materials. Following the parametric study [1] conducted on thin-walled spherical shells totally filled with materials having properties going from metal to plastic, acoustic measurements were performed on a fibreglass spherical shell filled with a low-shear-speed epoxy resin. Preliminary measurements were conducted also on the void shell before filling and on a solid sphere of the same material as the interior. The shell material is randomly-distributed (hence approximately isotropic) fibreglass.

Acoustic measurements were in the broadband range of *ka* = 5-30 (with *k* being the water wavenumber and *a* the object dimension) which is suitable for the excitation of a number of elastic waves. In this *ka* range a randomly distributed fibre is assumed to be sufficiently isotropic and homogeneous to be acoustically modelled with an analytical tool [1]. The same can be assumed for the epoxy resin filler, although air micro-bubbles can be trapped during manufacturing.

Preliminary measurements of the solid resin sphere and of the void fibreglass shell allowed the inversion of the material parameters, namely of shear and compressional speeds and their sound attenuations (Section 2). Inversion is based on an initial guess of possible ranges of values achieved from the analysis (identification of supported waves and estimation of their echoes' arrival time) of the elastic echo structure. The optimal set of parameters is determined by minimizing the difference between the measured time response and a set of possible analytic solutions, one for each combination of the set of parameters.

Given the parameter estimates of the constituent materials, the measurement of the solid-filled shell (Section 3) aimed to verify whether the elastic waves predicted by analytical models were detectable. Also it was useful to check the sphere symmetry and to investigate whether perfect contact at the filler-shell interface (as assumed in past simulation studies [1]) was achieved during manufacturing. This analysis revealed inhomogeneities of the interior (in particular an extended air pocket), which were later confirmed by X-ray CT scan and ultrasound measurements. Conclusions are drawn in Section 4.

2. PRELIMINARY TANK MEASUREMENTS. INVERSION OF MATERIAL PROPERTIES

Backscattered responses by a fibreglass empty spherical shell (outer radius *a*=6.25cm, thickness d≈3mm) and by a solid sphere of epoxy resin (radius *a*=6cm) were measured while suspended in the middle of a tank 4.5m x 3m x 2.3 m of size. For suspension the objects were tied up by a thin nylon wire net, fixed to the object by several resin drops. The source (Reson TC2138) was located at mid water at one end of the tank. Its sensitivity is roughly flat between 40 and 100 kHz but the Signal-to-Noise Ratio (SNR) was good enough that data could be used from about 15 to 100 kHz. The receiver was an omnidirectional hydrophone with roughly flat response between 1 and 300 kHz. It was located between transmitter and target on the transmission axis in such a way to minimize the surface and bottom interference. The directionality of the source (having 30^o of beamwidth null to null at 50 kHz and sidelobes -20 dB down) allowed the complete illumination of the objects without strong interferences with the tank boundaries and the water surface. The residual reverberation was mitigated by subtracting a coherent average of 20 pings of scattering from the tank boundaries. Data were coherently averaged over 20 pings and equalized in the spectral domain by using the measurement of the transmitted pulse on the same hydrophone. The Target Strength (TS) data were hamming-windowed before applying an inverse Fourier transform in order to get a smooth time response.

In the investigated bandwidth, from measurements at different aspects (with respect to an arbitrary zero) the shell appeared homogeneous (Fig.1(a)). Very low (below 30 kHz) and very high (above 90 kHz) frequency discrepancies are possibly due to lower SNR level at the extremes of the source bandwidth. Figure 1(b) shows the result of model-data comparison after acoustic inversion of the material parameters. The estimated values are indicated in the figure title. The estimation error on the speeds is of the order of ± 50 m/s, on the attenuations around ± 0.2 dB/λ. The echoes following the temporal front echo and the dips in the TS plots are due to the S_0 Lamb-type wave. The disagreement between 50 and 90 kHz is possibly due to increasing relevance of the fibre structure details as frequency increases, which may perturb the propagation of the S_0 wave, being shell-borne.

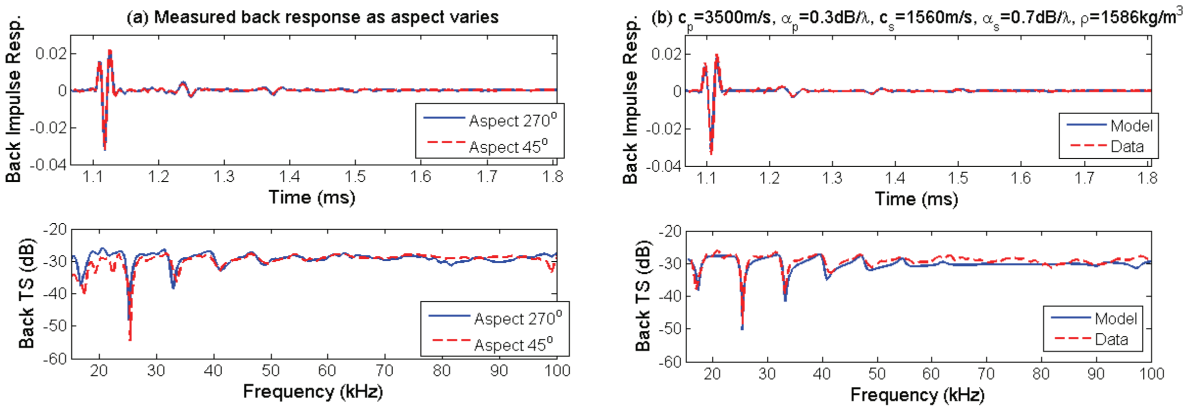

Fig.1: Empty fibreglass shell. (a) Backscattered data at two aspects. (b) Model-data comparison (data at aspect=270°) after material parameter inversion.

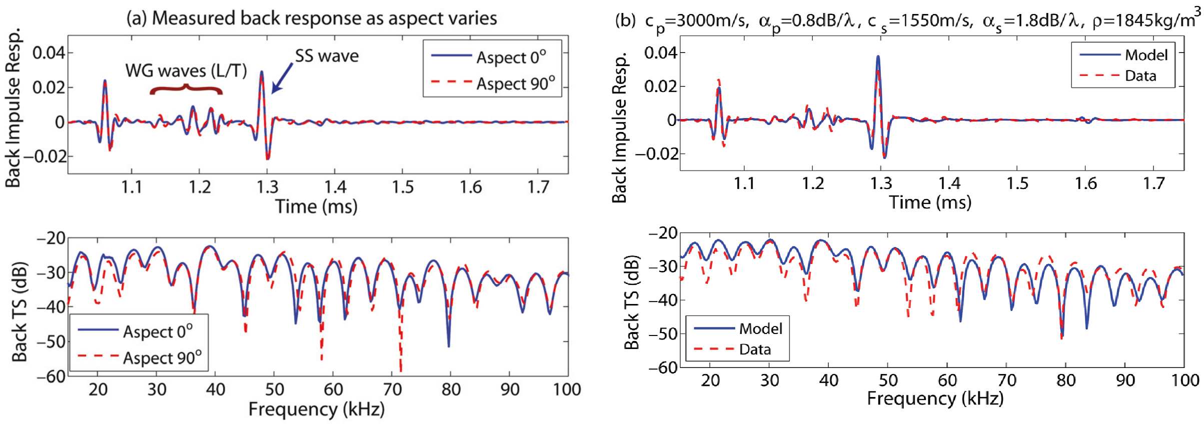

Fig.2: Solid epoxy-resin sphere. (a) Backscattered data. Elastic wave analysis is applied to the temporal response. WG stays for Whispering-Gallery, L for longitudinal, T for transversal, SS for Scholte-Stoneley. (b) Model-data comparison (data at aspect=90°).

Figure 2(a) shows the data comparison of the solid resin sphere insonified at different aspects. The sphere appears homogeneous and isotropic in the bandwidth. The model-data comparison achieved after acoustic inversion (Fig. 2(b)) shows a generally good agreement. The inversion results are indicated in the figure. The speeds estimation error is of the order of ± 30 m/s, lower than in the shell case since here more elastic waves are excited, providing redundant information, hence more robust estimation. The main discrepancy in the time domain is in the level of the Scholte-Stoneley (SS) surface wave echo arriving at t=1.3 ms, and corresponding to a mismatch in the low-frequency Target Strength level. This is probably due to partial diffraction of the wave at the small protrusions of the suspension system.

3. MEASUREMENTS OF A RESIN-FILLED FIBREGLASS SHELL

The void shell was then filled with the same material of the solid sphere and measured under the same configuration as described in Sect. 2. The epoxy-resin is originally liquid; in order to maintain isothermal chemical reaction it must be cast layer by layer, each layer needing a predefined time to solidify. A comparison of measurements at aspects 0^o and 90^o (Fig. 3(a)-top) shows phase reversal of the front echo and of other small echoes and disagreement in the level of the first SS wave echo, which is higher when the front echo is reversed. Data at aspect 180^o (Fig. 3(a)-top) is perfectly in phase with the ones at aspect 90^o, but the SS echo has almost disappeared and new internal reflections come around 1.35 ms, possibly coming from the filler's local inhomogeneities. The front phase reversal in the data at aspect 0^o implies the presence of a considerable air bubble inter-layer immediately behind the shell part hit by the incident pulse. In the data at aspect 90^o and 180^o (Fig. 3(a)-bottom), the filler appears in contact with the shell in the illuminated part of the sphere (front), whereas the lower level of the SS wave echo may indicate that now the air pocket is in the rear part, where this wave travels before its first back re-radiation. Hence the sphere is evidently neither 3D-symmetric nor homogeneous.

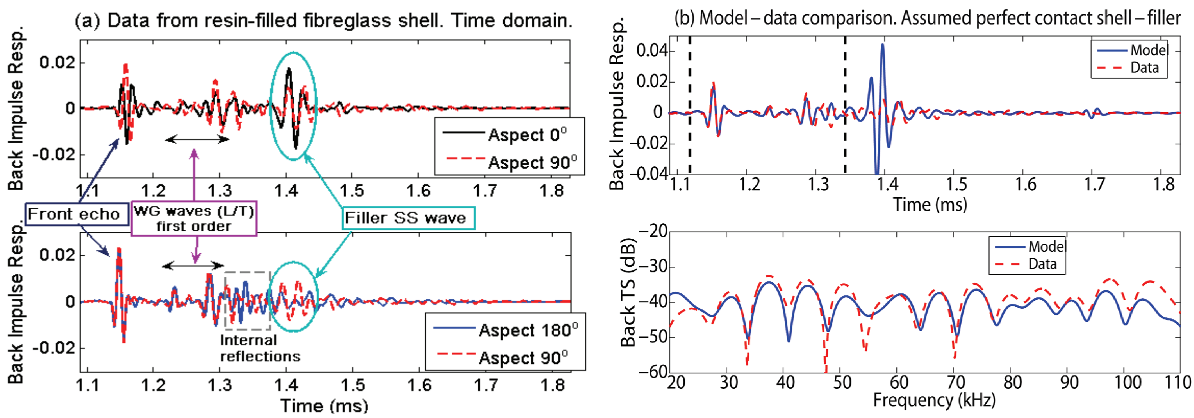

Fig.3: Epoxy-resin-filled fibreglass shell. (a) Comparison of backscattered data at various aspects. Wave analysis is applied. (b) Model-data comparison (data at aspect=90^o) under assumption of perfect-bonded boundary at the shell-filler interface.

The time comparison (Fig. 3(b)) of the data at aspect 90^o to an analytical model, that was fed with the material parameters estimated in Sect. 2 and assumes perfect contact [1], shows a good matching of the first arrivals of the Whispering-Gallery waves, which means that the filler properties are still valid. The air pocket considerably affects both the phase and the amplitude of the SS wave echo, as expected by theory [2]. The comparison in frequency is limited to the elastic scattering component of the response within the two black dashed lines. Due to the asymmetry of the sphere interior, other attempts to apply analytical models with different hypotheses of boundary conditions at the filler-shell interface (such as pure transverse slip [2], discontinuity of either tangential or radial, or both displacements [3]) were unsuccessful to properly model the SS wave echo. The only model really solving this problem is expected to be fully 3D, but would need a precise knowledge of the size and distribution of the inhomogeneities (air pockets).

3.1. Additional NDT tests

Confirmation of the presence of an extended thin air pocket between shell and filler came from additional independent measurements. The X-ray CT scan of the sphere (Fig. 4), performed with a GE Medical Systems multislice scanner at the Radiology Branch of the Carrara Hospital, revealed the presence of a wide inter-layer of air of about 1.5mm maximum thickness (Fig. 4(right)).

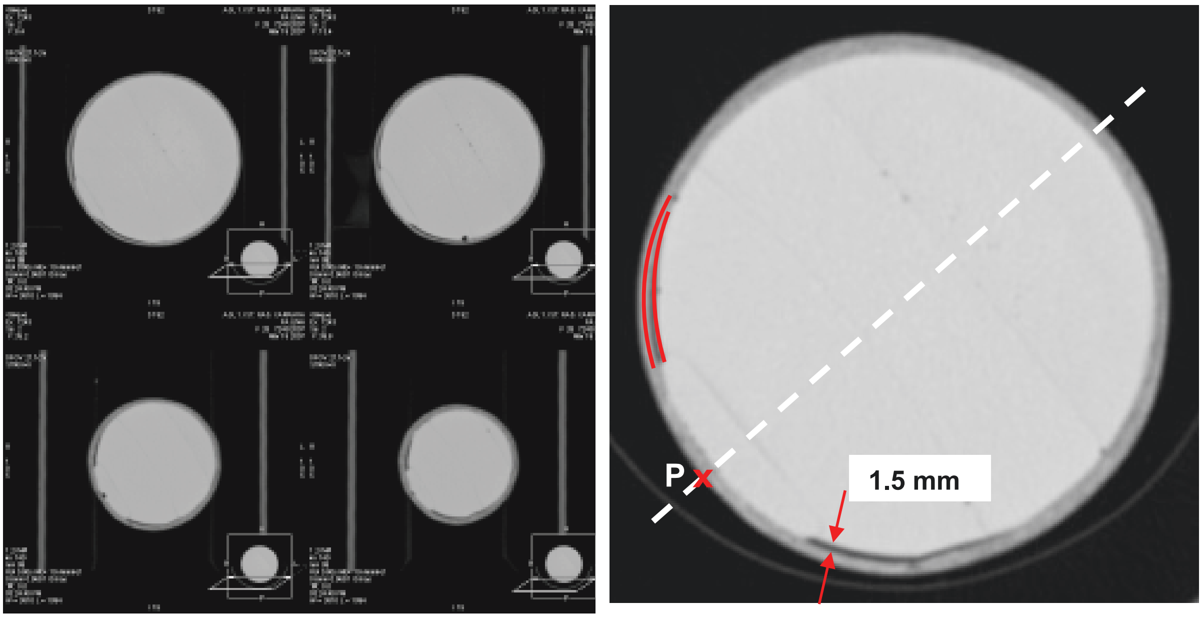

Fig.4: CT scan of the resin-filled shell: (left) A set of 4 horizontal slices; (right) One vertical slice. The sphere section looks roughly symmetric with respect to superimposed dashed line (axis) passing through the pole P. Two red lines show the boundaries of the air pocket section at one side of the axis. At the other side the air pocket maximum thickness is measured. The shell was filled in 5 steps, as the interfaces between adjacent layers can be detected. Small air bubbles can be also detected.

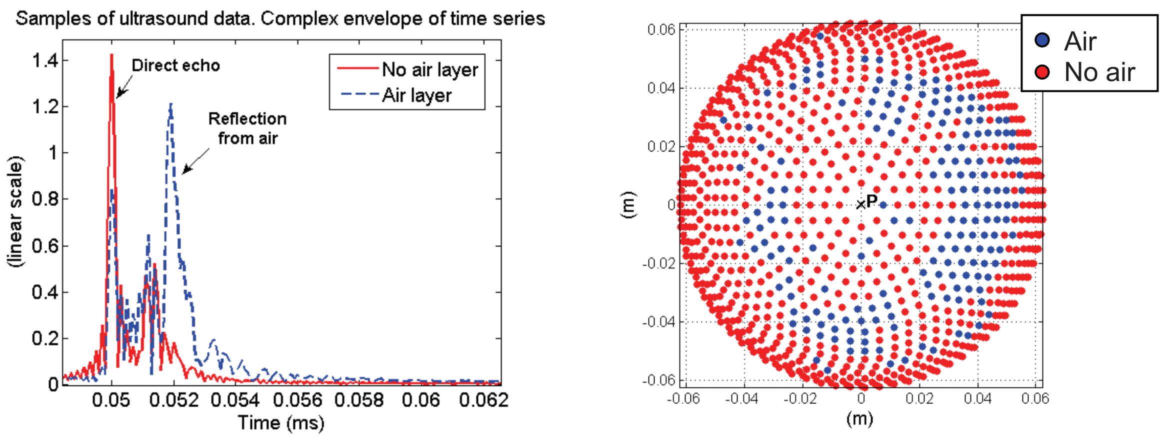

Fig.5: Ultrasound measurements of the resin-filled shell: (left) Data comparison in presence and absence of air at the other side of the shell wall; (right) 3D mapping of the air pockets: top view. The black cross labelled P *locates the pole of Fig. 4 (right).*

Ultrasound scanning was conducted at 5 MHz with a Krautkramer transducer on the surface of the hemisphere where the CT scan localized the air pocket (Fig. 5). A strong echo is reflected back from the internal interface of the shell wall only if there is air at the other side; otherwise the impedance between the shell and filler materials is too low to give a significant reflection. This measurement allowed us to precisely (5mm resolution) estimate the geometry of the main air pocket around the sphere. Its shape is a sort of ring probably caused by the detachment from the shell wall of the filler's forth layer during its solidification. The roughly axisymmetric shape of this air pocket may allow us to apply the AXISCAT model [4] to refine the model-data comparison achievable by analytical tools.

4. CONCLUSIONS

A series of acoustic measurements were conducted in a tank on an epoxy-resin-filled fibreglass spherical shell and its basic parts (filler sphere and void shell). The data were analyzed in terms of supported elastic waves and compared to analytical models. Acoustic inversion was applied to estimate the material properties. The main result obtained was that the resin-filled shell had an extended air pocket of about 1.5mm of maximum thickness, whereas an approximately perfect contact was expected between filler and shell due to a careful manufacturing process. The flaw was independently measured by X-ray CT scan and ultrasound measurement of the object. This implies that it is not trivial to conduct controlled scattering measurements in the case of plastic composite objects, even if carefully manufactured. Furthermore, the results obtained show how much the low-frequency response of an object may change due to internal differences deriving from manufacturing flaws. This defect was finally useful to prove the potential of low-frequency acoustic scattering analysis for non destructive testing applications.

5. ACKNOWLEDGEMENTS

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