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# Simulating Echo Responses from Arbitrary-Geometry Targets Using Mode Conversion Approach

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**Abstract** A computational method based on the spatial impulse response and on the discrete representation computational concept is proposed for the determination of the echo responses from arbitrary-geometry targets. A major contribution of this paper is the development of an improved version of the method considering a mode conversion approach at the reflector surface. It is supposed that each point of the transducer aperture can be considered as a source radiating hemispherical wave to the reflector. The local interaction with each of the hemispherical waves at the reflector surface can be modeled as a plane wave impinging on a planar surface, using the respective reflection coefficient. The method is valid for all field regions and can be performed for any excitation waveform radiated from an arbitrary acoustic aperture. The effects of target geometry, position, and material on both the amplitude and shape of the echo response are studied. The model is compared to experimental results obtained using broadband transducers together with, for instance, plane and cylindrical concave rectangular reflectors (aluminum, brass and acrylic) in a water medium.

## 1. INTRODUCTION

In ultrasonic nondestructive evaluation using the transmit-receive mode (or pulse-echo mode), it is important to get more information of the defects in a structure such as size, shape, location and orientation, and acoustic impedance. However, the aim of describing the geometry and the physical properties of the targets at arbitrary position in a structure is very complicated, mainly in a realistic situation of interpretation and analysis of the measured echo signals. It is well known that the echo waveforms are deformed due to the diffraction effects, the geometry and acoustic impedance of the targets, and the acoustic absorption of the medium.

An experimental study to classify echoes reflected from standard defects was defined by using classifier databases of the waveform features [1]. Nevertheless, the implementation is expensive and requires collecting several experimental data *a priori* using a lot of samples and transducers with different frequencies. Another possibility is to substitute experimental measurements for theoretical values obtained by computational simulations. Therefore, many methods for simulating echo responses from targets were implemented to improve the prediction of the signal distortion. For example, several computational methods are based on the impulse response method [2]-[6], the angular spectrum technique [7], the finite element method [8], and the optical geometry study [9]-[10]. A lot of these methods are extensively studied in the scientific literature and some of them could result in a realistic simulation in a nondestructive evaluation of materials, but this simulation will demand a significant increase in the computation time.

In this article, a computational method is proposed to predict the echo response from arbitrary-geometry targets of different materials, considering the case of propagation in a nonattenuating fluid. The method is based on a model to calculate the longitudinal wave evolution caused by interfaces, as recently described by Buiochi *et al*. [11]. The model features a three-dimensional analysis, which is based on the spatial impulse response [12] and on the discrete representation computational concept [13]-[14]. The method operates by dividing the transmitted aperture, the reflector surface, and the receiver aperture into elementary areas. First, the velocity potential impulse response is calculated in each of the elementary areas of the reflector using the Rayleigh integral. Second, the reflected velocity potential impulse response is calculated by applying the Rayleigh-Sommerfeld integral to the reflector surface. Finally, the spatial-average acoustic pressure over the surface of the receiver is determined by a temporal convolution between the excitation signal and the spatial-average reflected velocity potential impulse response.

A good physical understanding of the method implemented here is provided by the Huygen's principle. The emitter and the target are discretized into elementary areas as point sources generating hemispherical waves. Each point source on the reflector is calculated by the superposition of hemispherical waves radiated at each point of the emitter and the application of the reflection coefficient in each incident hemispherical wave at the reflector surface. This permits to calculate the acoustic pressure on the receiver from these elementary point sources on the reflector. An illustration of this idea is shown in Fig. 1, using transmit-receive mode.

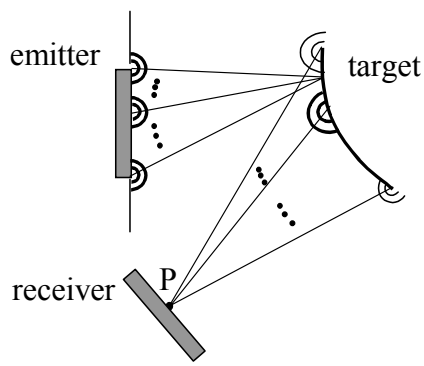


*Figure 1: Construction of point sources on the reflector surface from hemispherical waves and the acoustic pressure at point P on the receiver according to Huygens.*

## 2. THEORY

The analytical solution of the computational method proposed by Buiochi *et al*. [11], which determines the acoustic field through interface, is very easy to calculate the echo responses using the same theoretical concepts. The theoretical concepts are based on the Rayleigh and the Rayleigh-Sommerfeld integrals, respectively, assuming an emitter embedded in a rigid baffle and a target surrounded by a soft baffle [15]. The approach we are using in this work deals with a planar emitter and planar or slightly curved targets, where these integrals can represent the radiation [16]-[17].

Consider the geometry depicted in Fig. 2 for determining the transmit-receive mode echo response. An emitter transmits an acoustic pulse into an isotropic medium that contains a defect (reflector). This transmitted pulse travels to the reflector, where part of it is reflected and returns to the receiver. The conversion mode is included in the method considering each incident hemispherical wave at the reflector as a plane wave. Furthermore, we regard that the receiver does not interfere with the acoustic beam. In Fig. 2, representing a general case, the apertures of the emitter and the receiver are not parallel to the face of the reflector.

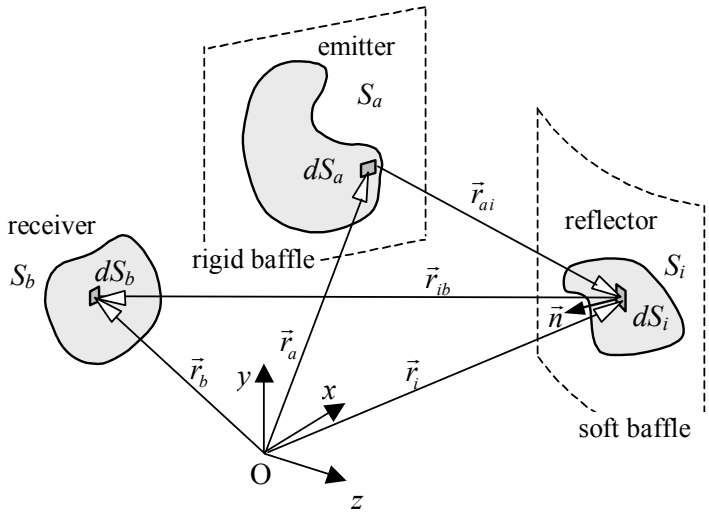


*Figure 2: Arbitrary geometry used to determine the transmit-receive mode echo response.*

Using the Buiochi *et al*. solution [11] for the transmit-receive mode, we consider the aperture of the emitter to be a uniform piston, and the reflector to be a radiated surface after the interaction of the incident waves with it. Firstly, the velocity potential impulse response is determined from the emitter on each point of the reflector using the Rayleigh integral and considering the reflection coefficient:

$$h_a(\vec{r}_i,t) = \int_{S_a} \frac{C^R(\vec{r}_{ai},\vec{n})\,\delta(t - r_{ai}/c)}{2\pi\, r_{ai}}\, dS_a \tag{1}$$

where $S_a$ is the surface of the emitter; $r_{ai}$ is the distance from the elementary area $dS_a$ located at $\vec{r}_a$ to the point located at $\vec{r}_i$; $c$ is the acoustic propagation velocity in the medium; $C^R(\vec{r}_{ai},\vec{n})$ is the reflection coefficient at the reflector that defines the relation between the

pressure wave immediately before and after the interaction with the reflector surface for each incident hemispherical wave.

The incident hemispherical waves on each point of the surface can be approached by locally plane waves, considering that the distance between a point of the emitter and a point of the target is large compared with the wavelength. Using the angle of incidence defined by the vectors $\vec{r}_{ai}$ and $\vec{n}$ to each locally plane wave, the reflection coefficients are determined by the transmission-line models for plane interfaces developed by Oliner [18]. This model establishes an analogy between transmission lines and acoustic waves for several interfaces. This approach makes the enormous number of methods to solve transmission line problems available to solve acoustic waves problems in a systematic, simple, and direct manner.

Now using the Rayleigh-Sommerfeld integral, we calculate the velocity potential impulse response on each point of the receptor, which is defined by:

$$h(\vec{r}_b,t) = \frac{1}{2\pi c}\int_{S_i} \frac{\cos(\vec{r}_{ib},\vec{n})}{r_{ib}} \frac{\partial}{\partial t} h_a(\vec{r}_i, t - \frac{r_{ib}}{c})\, dS_i \tag{2}$$

where $S_i$ is the surface of the reflector; $r_{ib}$ is the distance from the elementary area $dS_i$ located at $\vec{r}_i$ to the point located at $\vec{r}_b$ in the receptor; $\cos(\vec{r}_{ib},\vec{n})$ is the cosine of the angle between the normal vector $\vec{n}$ and the vector $\vec{r}_{ib}$.

Finally, the spatial-average acoustic pressure $\langle p(\vec{r}_b,t)\rangle$ over the surface of the finite receiver is calculated by a temporal convolution between the excitation signal $v(t)$ and the spatial-average impulse response $\langle h(\vec{r}_b,t)\rangle$:

$$\langle p(\vec{r}_b,t)\rangle = \rho \frac{\partial v(t)}{\partial t} * \langle h(\vec{r}_b,t)\rangle \tag{3}$$

where $\rho$ is the density of the propagation medium, and the symbol $\langle \quad \rangle$ denotes the spatial average over the surface of the finite receiver $S_b$. The spatial-average impulse response is given by:

$$\langle h(\vec{r}_b,t)\rangle = \frac{1}{S_b}\int_{S_b} h(\vec{r}_b,t)\, dS_b \tag{4}$$

## 3. COMPUTATIONAL METHOD

In this work, the proposed solution is an approximated method that operates by dividing the emitter aperture, the reflector surface, and the receiver aperture into elementary areas. The

radiated and reflected acoustic fields result from the superposition of the hemispherical waves generated from each elementary area of the emitter and the reflector, respectively. The accuracy of the computational method depends on temporal and spatial samplings and can be obtained as required [11]. Better resolution is obtained with smaller temporal samplings, and increased precision results from smaller spatial samplings. Therefore, the computation time increase if these two aspects increase, thus a balance should be found.

The method is divided in three steps. In a first step, the velocity potential impulse response $h_a(\vec{r}_i, t)$ is calculated from (1) at the reflector surface. In each of the elementary areas of the reflector, the impulse response function is affected by the corresponding reflection coefficients. In a second step, the velocity potential impulse response $h(\vec{r}_b, t)$ is calculated from (2) on each elementary area of the receptor. In a third step, the spatial-average impulse response $\langle h(\vec{r}_b, t) \rangle$ is obtained by (4), and the spatial-average acoustic pressure $\langle p(\vec{r}_b, t) \rangle$ is calculated from (3).

## 4. RESULTS

In this section an implementation of the computational method was performed to test the validity to determine echo response from finite-sized targets, using theoretical and experimental results obtained by other authors, which can be used by a benchmark. First, our simulated results were compared with McLaren and Weight's results [3], using planar disk targets interrogated by a signal from a circular emitter with parallel face. In addition, Lhémery and Raillon's results [5] of predicted and measured echo responses from tilted planar disk targets were also compared with our results. Another way to validate the method was to compare the theoretical results and some experimental cases obtained by us as, for instance, plane and cylindrical concave rectangular targets with different materials.

### 4.1 Parallel Planar Disk Targets

Fig. 3 indicates schematically the physical arrangement used by McLaren and Weight [3] with on- or off-axis planar disk targets parallel to the emitter. A coordinate $X$ and an axial distance $Z$ define the position of the target relative to the referential $\mathrm{O}\,x\,z$ located at the center of the transducer. The measurements were obtained by using a circular emitter with diameter 19mm and central frequency 2MHz, and brass targets immersed in water.

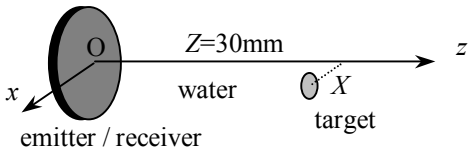


*Figure 3: The geometry used to calculate the pulse-echo mode responses with parallel faces.*

The simulated echoes were determined by convolving our respective calculated spatial-average impulse response from (4) with the plane wave measured by McLaren and Weight, obtained graphically by us. Figs. 4 and 5 show our simulated echo responses from 0.8-, 2-,

and 8-mm-diam targets at $Z$=30mm, either on-axis (Fig. 4) or $X$=2 mm off the axis (Fig. 5). The McLaren and Weight's calculated and measured echoes are shown in [3], [5]. The amplitude scales have been normalized to that for the axial 0.8-mm-dim target. In these figures, the relative amplitudes are shown in dB.

We can verify that the computational method predicts accurately the theoretical and experimental echo responses obtained by McLaren and Weight, both qualitatively (shape of the echo waveform) and quantitatively (relative amplitude).

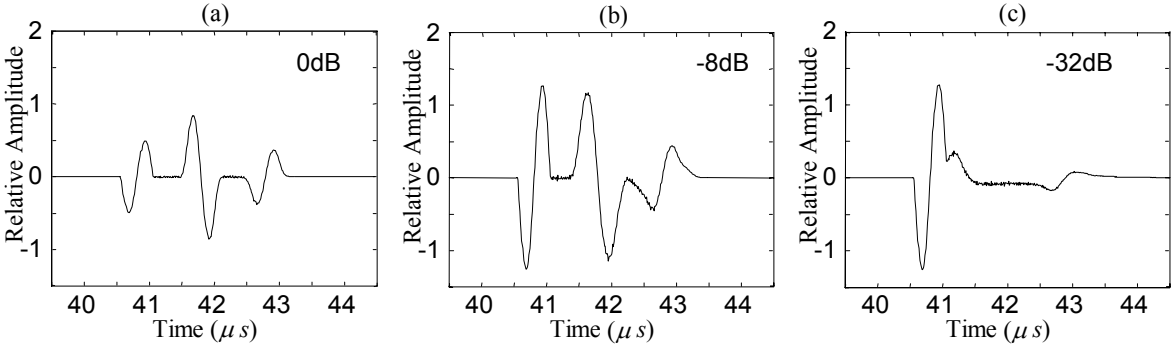


*Figure 4: Simulated echo responses from (a) 0.8-, (b) 2-, and (c) 8-mm-diam targets at Z=30mm on-axis.*

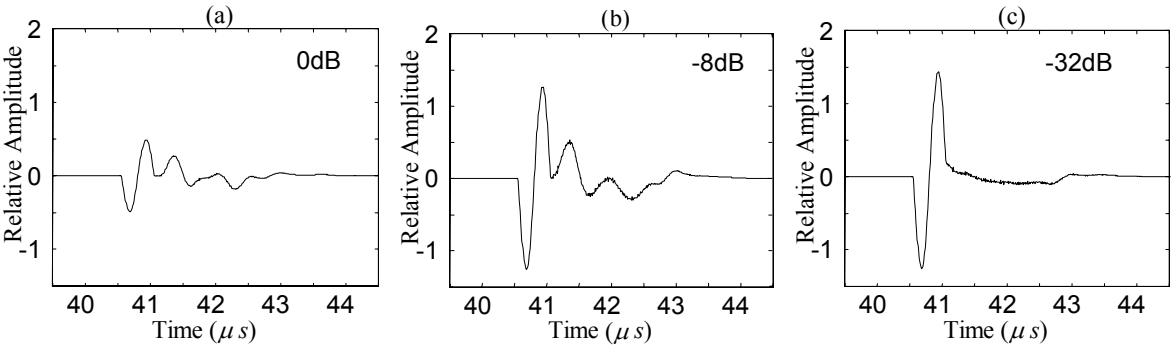


*Figure 5: Same as in Fig. 4 but for* X=*2mm off-axis.*

## 4.2 Tilted Planar Disk Targets

Reflected echoes from tilted planar disk targets were obtained by Lhémery and Raillon [5], and were carried out using the same previous circular emitter, diameter 19mm and central frequency 2MHz. Fig. 6 shows schematically the physical arrangement used here to place the tilted planar disk targets on-axis in front of the transducer. An angular orientation $\alpha$ and an axial distance $Z$ define the position of the target relative to the referential $\mathrm{O}xz$. The material of the targets is brass with diameters 4 and 10mm, immersed in water. The excitation signal used in our case was also obtained graphically from Lhémery and Raillon's results, considering only the plane wave component.

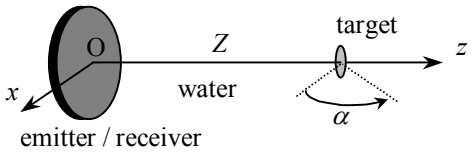


*Figure 6: The geometry used to calculate the pulse-echo mode responses with tilted faces.*

Again, we only present here our simulated results. Fig. 7 shows the pulse-echo mode responses for the 4-mm-diam target at *Z*=35mm (near field) on-axis, normally aligned and tilted by $10^{\circ}$ and $20^{\circ}$. Fig. 8 shows the echo responses for the 10-mm-diam target at *Z*=120mm (far field) on-axis for the same angles. The simulated echoes are represented graphically to the same relative amplitude scales, which are normalized to that for the axial normally aligned, 10-mm-diam target at *Z*=120mm. The relative amplitudes are shown in dB in these figures.

Here again, the computational method allows a very accurate prediction of experimental echo responses. Figs. 7 and 8 show that the results are in agreement with Lhémery and Raillon's results.

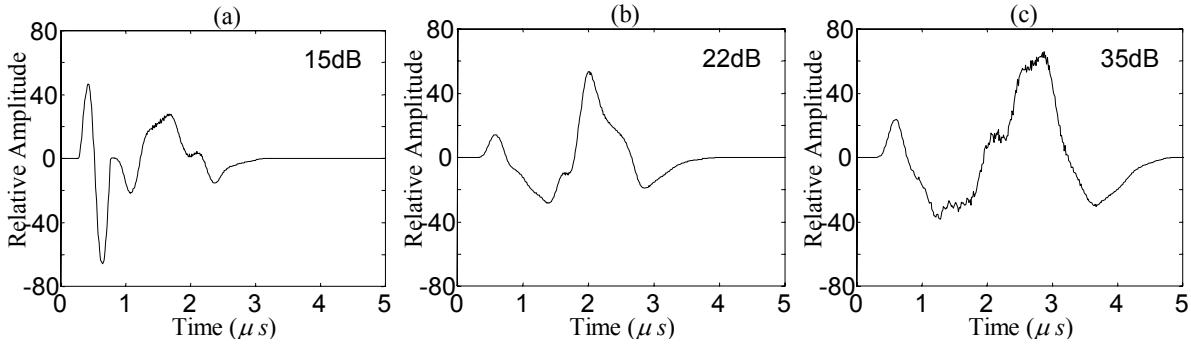


*Figure 7: Simulated echo responses from a 4-mm-diam target at Z=35mm on-axis (a) normally aligned, or tilted (b)* $10^{\circ}$*, and (c)* $20^{\circ}$ *with respect to the emitter.*

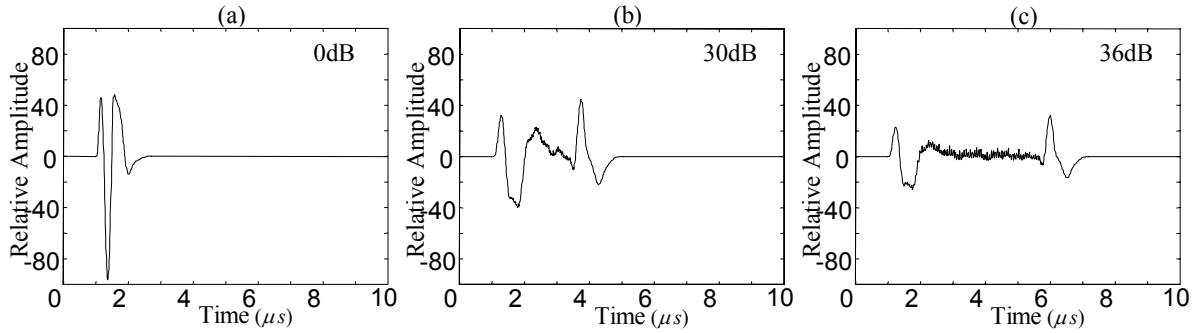


*Figure 8: Same as in Fig. 7 but for a 10-mm-diam target at Z=120mm on-axis.*

### 4.3 Parallel Rectangular Targets of Differing Materials

For the rectangular geometry targets, a plane surface and a cylindrical concave surface were used. The dimensions of both surfaces of the targets are 10 × 10mm, and the curvature radius of the cylindrical concave surface is 60mm. The materials of the targets are aluminum, brass, and acrylic. The measurements were carried out using a 19-mm-diam transducer with central

frequency 1.5MHz, immersed in water. The targets normally aligned are centered on the acoustic axis of the emitter/receiver, and the axial distance is $Z$=35mm, as shown in Fig. 9.

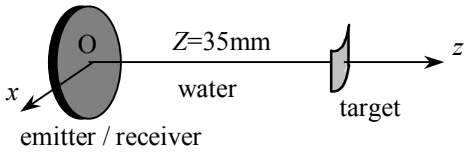


*Figure 9: The geometry used to calculate the pulse-echo mode responses from rectangular geometry with different materials.*

Fig. 10 shows measured and simulated echo responses for three plane rectangular target materials: aluminum, brass, and acrylic. Fig. 11 shows the results for the cylindrical concave rectangular target for the same materials as in Fig. 10. Excitation and reception conditions are identical in all measurements presented here. The pressure amplitudes have been normalized by the maximum value recorded for the plane rectangular target machined from aluminum. Figures 10 and 11 show that differing materials of a target of identical geometry do not affect the shape of the echo response. However, they affect the echo amplitude.

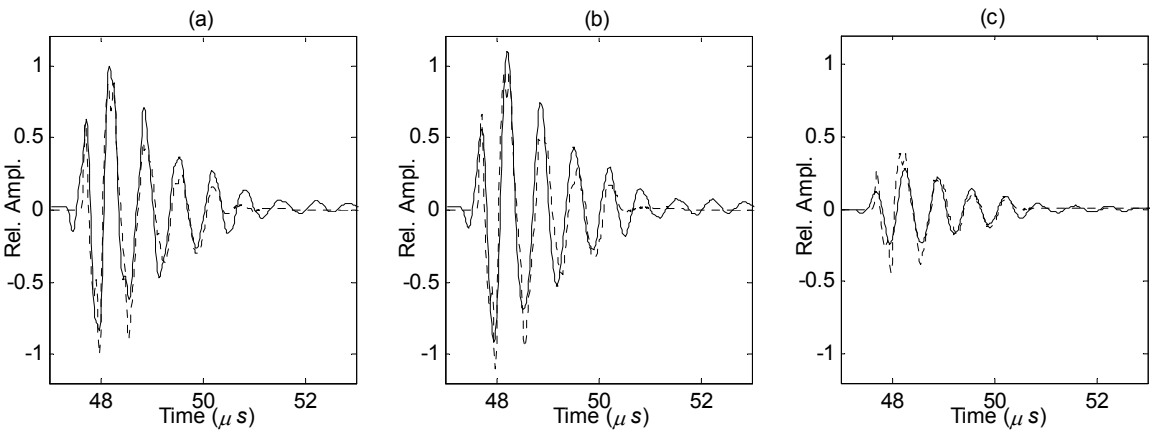


*Figure 10: Comparison of the measured (solid lines) and the simulated (dotted lines) echo responses from plane rectangular target of aluminum, (b) brass, and (c) acrylic materials on-axis.*

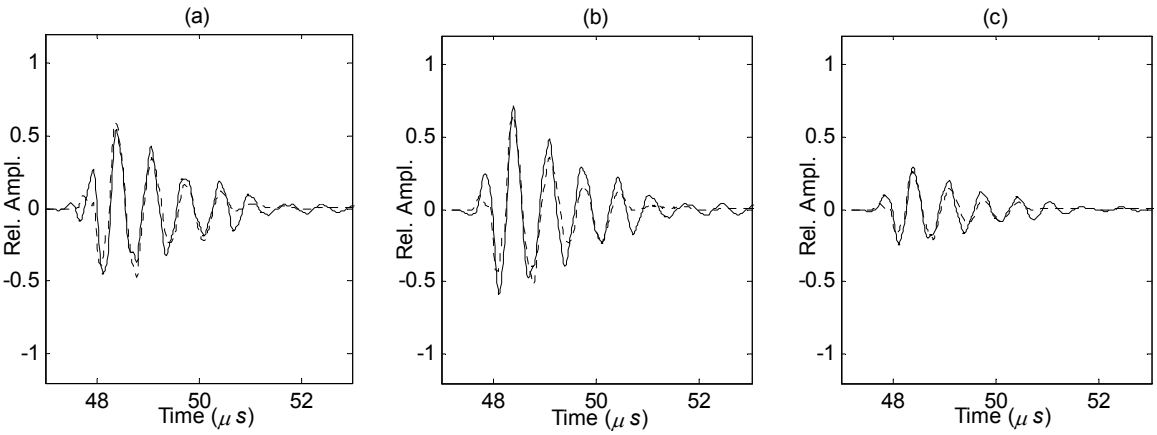


*Figure 11: Same as in Fig. 10 but for cylindrical concave rectangular target.*

## 5. CONCLUSION

A three-dimensional computational method was proposed for the calculation of the echo responses from finite-sized targets of complex geometry and arbitrary impedance. The method is valid for all the field regions and can be performed for any excitation waveform radiated from an arbitrary acoustic aperture. Comparison of experimental and theoretical echo responses obtained by other and present authors shows the accuracy of the method, both qualitatively and quantitatively. This method is general and can accurately predict the shape and the relative amplitude of the echo responses from different materials, taking into account the mode conversion at the target surface.

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