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Minimization of internal reverberation in acoustic windows used in US inspection systems by numerical simulation

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Abstract

Most ultrasonic tools for the inspection of pipelines or bore-holes consist of a transducer, separated from the exterior by an acoustic window. This acoustic window protects the device from the potentially hostile exterior and is part of the mechanical construction. Therefore the acoustic window is positioned between the transducer and the region of interest. Due to mechanical constraints and acoustic impedance differences between the window and the in- exterior mediums, the acoustic window will produce unwanted internal reflections. The amplitude of these reflections is normally much higher than the background noise level. These reflections hamper proper defect analysis of the pipeline, such as wall thickness loss.

This study is performed to reduce these reflections, while fulfilling the mechanical specifications of the acoustic window. With UMASIS, a fully elastic 2D finite difference modeling tool, several configurations are simulated. UMASIS is a very powerful tool for modeling and interpreting modeling results. The thickness, orientation and shape of the acoustic window are varied. The modeled response provides accurate information about the dominant contributions to the internal reflections. The snapshots generated with UMASIS, enable us to pinpoint the causes of reflection. This drastically decreases the development time of the acoustical window and allows a significant reduction of the distortion of the acoustic window.

Keywords: optimization, ultrasonic inspection, pipeline, modeling

1. Background

Ultrasonic tools for the inspection of pipelines or bore-holes generally consist of a rotating transducer in lubrication oil. The transducer and oil are enclosed by an acoustic window. This acoustic window protects the dedicated device from the exterior. Especially borehole scanners must operate at high pressure and high temperature and in harsh conditions. For most pigs and borehole scanners the acoustic window is part of the mechanical construction. This restricts the dimensions and material properties of the acoustic window. Due to these mechanical constraints and acoustic impedance differences between the window and the in- exterior media, the acoustic window will produce unwanted reflections and internal reverberations (Figure 1). The amplitude of these disturbing signals is normally much higher than the background noise level [1]. These distortions hamper proper defect analysis of the pipeline. For wall thickness loss, internal reverberation and SNR are important aspects for accurate thickness determination.

It is of our interest to reduce the reflections and internal reverberations by proper design. For this purpose several simulations are performed. For the simulations UMASIS is used. UMASIS is a fully elastic 2D finite difference modeling tool which is a very powerful environment for modeling and interpreting [2, 3]. Especially the snapshots have proven to be very informative for interpretation of the results.

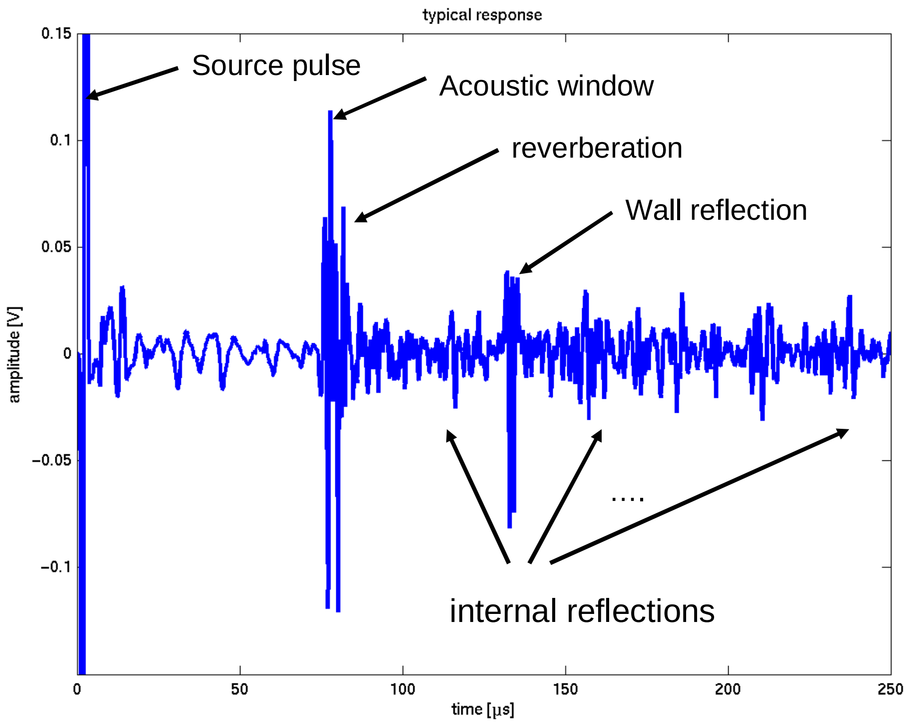


Figure 1 A typical distorted measurement from an ultrasonic inspection system using an acoustic window.

2. Theory

Due to acoustic impedance differences, the front and rear wall of the acoustic window cause reflection and transmission. Inside the acoustic window multiple reflection occurs when a perpendicular incoming plane wave propagates from layer 1 to layer 2, the reflection (R_{12}) and transmission (T_{12}) coefficients are given by [4]:

$$R_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \; T_{12} = \frac{2Z_2}{Z_2 + Z_1}, \qquad \textbf{(1)}$$

where $Z_1 = \rho_1 C_{p1}$ and $Z_2 = \rho_2 C_{p2}$ are the acoustic impedance of the first and second layer respectively. The reflection amplitude is directly proportional to the impedance differences between the two layers. Acoustic matching therefore is essential; although for this application only a limited number of materials is suitable. Reverberation inside the acoustic window can be described by the interaction between two layers [5]. For example, the reflection from and transmission through the acoustic window is given below:

$$R_{acousticwindow} = [R_{12} + \frac{T_{12}T_{21}W_2{}^2 R_{23}}{1 - R_{23}W_2{}^2 R_{21}}], \; T_{acousticwindow} = [\frac{T_{12}T_{23}W_2}{1 - R_{23}W_2{}^2 R_{21}}] \qquad (2)$$

where R_{23} represents the reflection at the rear wall of the acoustic window. R_{21} represents the internal front wall echo. T_{12}, T_{21} and T_{23} represent the transmission coefficients from one layer to another layer, specified by the indices. The propagation from the front wall to the rear wall or vice versa is given by $W_2 = e^{-j\frac{\omega}{C}d}$, where $\omega = 2\pi f$ is the circular frequency, d is the thickness of the acoustic window and C is the speed of sound in the acoustic window. Due to the propagation term the reflection and transmission coefficients are frequency dependent (Figure 2).

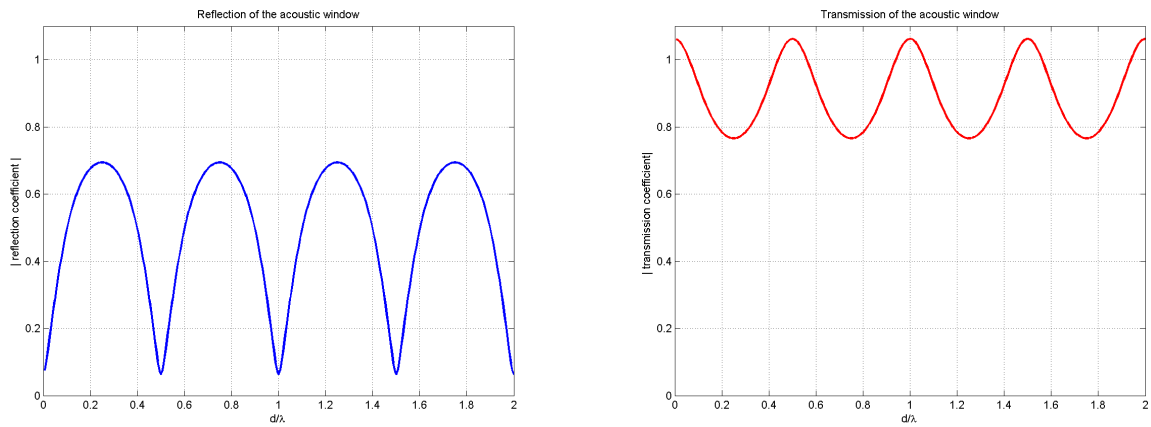


Figure 2 Frequent dependent reflection (left) and transmission (right) coefficients of the acoustic window.

If the plane wave is not arriving perpendicular to the surface of the acoustic window, refraction and wave conversion will take place. Due to refraction, the reflection and transmission coefficients will become angle dependent. The conversion from longitudinal waves to shear waves can be described by the Zoeppritz equations or by approximations as described by Aki & Richards [6, 7]. Depending on the material properties and the angle of incidence, the amount of conversion varies. The amplitude of the longitudinal and converted shear wave is indicated in Figure 3 for the first layer. The reflection and transmission of the longitudinal waves are almost constant for angles up to 20 degrees. In this range, the wave conversion is directly proportional to the angle of incidence.

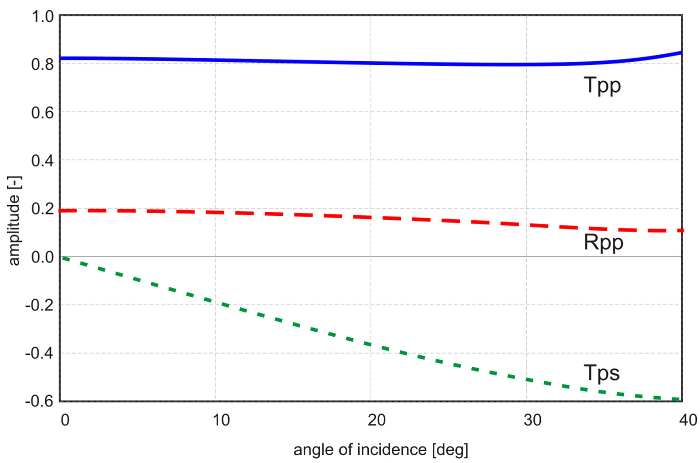


Figure 3 Angle dependent transmission (Tpp and Tps) and reflection coefficient (Rpp) for the transition from the interior to the acoustic window according to Crewes [7].

3. Approach

A simplified model of the ultrasonic tool is defined. The model consists of a transducer, positioned in oil and separated from water by the acoustic window. In the watery exterior a thick steel reflector is positioned. The model is depicted in Figure 4a and the material properties are listed in Table 1. As can easily be seen in the model, internal reflections can occur between the transducer and the acoustic window (Figure 4b). Reverberations occur inside the acoustic window (Figure 4c). External reflections take place between the outside of the acoustic window and the steel reflection (Figure 4d). The inspection tool can be designed such that multiples of the internal- and external reflections do not interfere with the region of interest.

This study focuses on the distortion do to the reflection of the acoustic window and the transmission through the window. For optimization of the inspection tool, the thickness, orientation and shape of the acoustic window are varied. The shape is altered by converting the rectangle acoustic window by a angles wedge (Figure 5). The nominal values and the variation range are listed in Table 2. With UMASIS ultrasonic several pulse-echo measurements are simulated.

Medium	**Cp [m/s]**	**Cs [m/s]**	**Rho [kg/m^3]**
Interior (oil)	1468	0	890
Exterior (water)	1480	0	1000
Acoustic window	2590	1730	1264
Reflector	5950	3200	7800

Table 1 Overview van model parameters

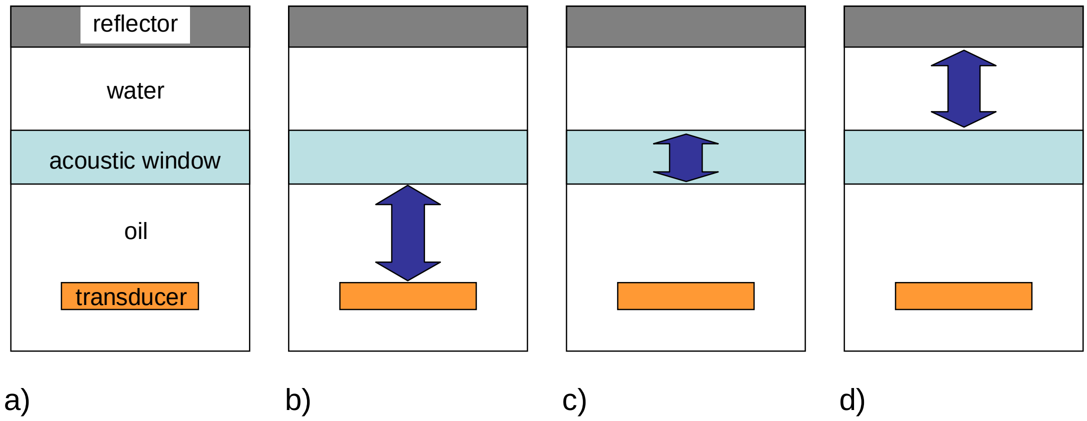


Figure 4 Standard configuration (a) and possible methods of distortion: internal reflections (b), reverberation in the acoustic window (c) and external reflections (d).

Parameter	**Variation**	**Nominal**
Thickness	0.2 - 3 mm	2 mm
Orientation	0 – 20 degrees	0 degrees
Wedge angle	0 – 10 degrees	0 degrees
Transducer diameter	-	27.5 mm, 10% cosine tapered
Transducer frequency	-	1.8 MHz
Simulation time	-	55 μs

Table 2 Overview of the applied variations

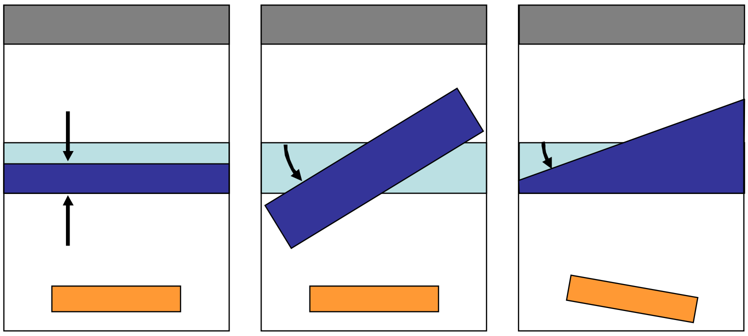


Figure 5 Variation to the standard configuration.

4. Finite difference model

For modeling UMASIS is used. UMASIS is a software tool that uses a wave equation based algorithm to calculate the full elastic wave field. This way all wave phenomena, like mode conversion, are automatically taken into account. Furthermore, the calculation of the wave field allows advanced visualization possibilities, like decomposition in pressure- and shear-waves (blue and red, respectively in Figure 7). This is very useful for the investigation of the origin of the distortions. UMASIS communicates over the Internet with a high performance computer cluster which reduces the need for extensive local computer resources.

Using the drawing capabilities of UMASIS multiple models are generated with various values for the investigated parameters (see Table 2 and Figure 5). The simulations were carried out on an external computer cluster and imported into UMASIS again to visualize and analyze the results [2, 3].

5. Data analysis

The results of UMASIS, the finite difference model, consist of a pulse-echo response and several snapshots. The snapshots are evaluated manually (Figure 6 and Figure 9). The envelopes of the simulated responses are visualized logarithmically (Figure 7 and Figure 8).

Figure 6a shows the emitted wavefield together with edge waves. When the wavefield propagates through the acoustic window, reverberation and wave conversion occur (Figure 6b-c). As can be seen in Figure 6a, the detected response from the steel reflector is distorted significantly.

As can be seen Figure 7, three main responses can be distinguished, the emitted wavefield followed by the reflection from the acoustic window and the reflection from the steel reflector. Notice the reverberation in the acoustic window on logarithmic scale. As expected, the reverberation levels decrease for higher multiple reflections. In the acoustic window, shear waves occur which are caused by wave-conversion of the edge waves originated from the transducer edges.

From the measured response, the distortion level from the reflected response (SNR_{REFL}) and the reverberation level (SNR_{rev}) are determined (Figure 7). The distortion level from the reflected response is calculated as the amplitude difference between the reflector amplitude and the noise level just before the response of the steel reflector. The reverberation level is determined by the amplitude difference between the peak amplitude of the reflector and the first internal echo in the acoustic window. Both SNR must be as high as possible for proper defect analysis.

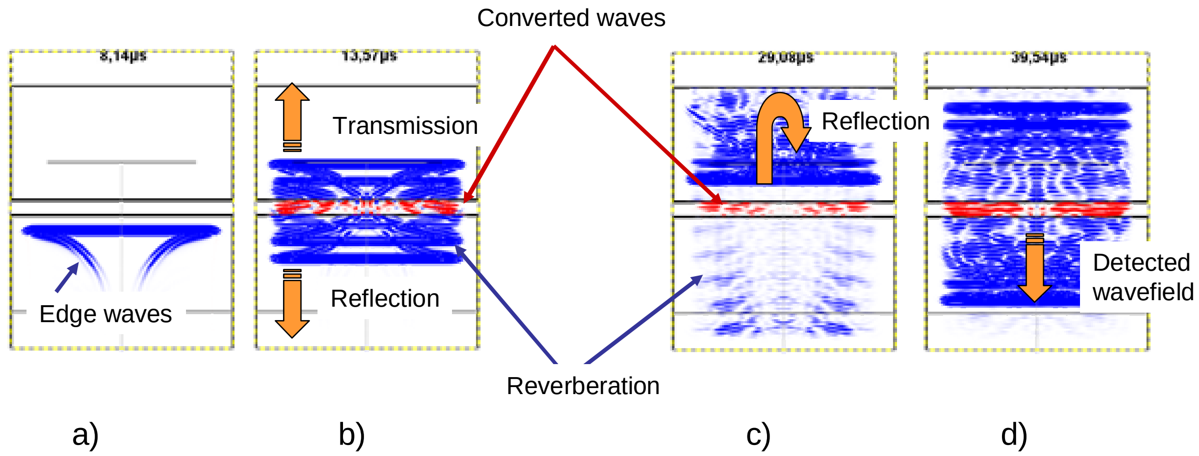


Figure 6 Characteristic snap shots of the default configuration: a) Just before the wavefield reaches the acoustic window. b) The reflected wavefield at the window and the transmitted wavefield through the window. c) The reflected wavefield at the steel reflector. d) The response from the steel reflector reaches the transducer.

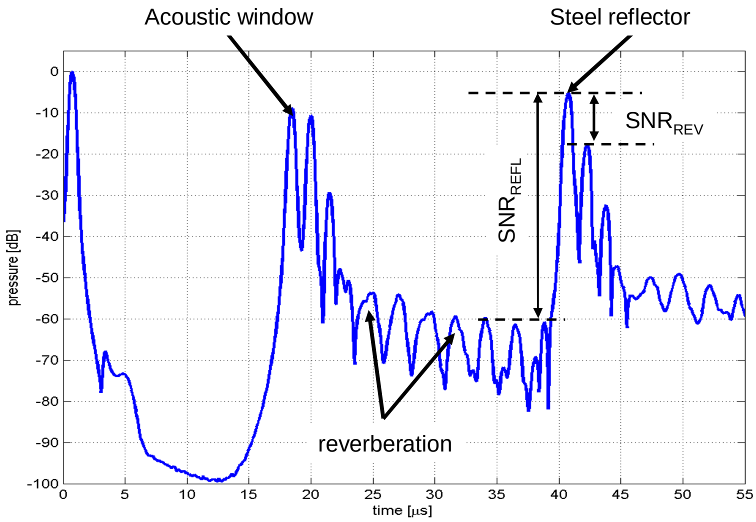


Figure 7 the logarithmically scaled response measured at the transducer of the default configuration.

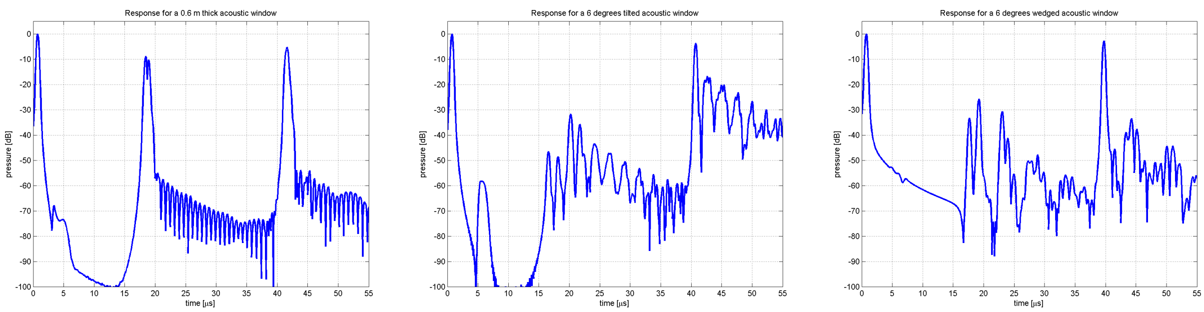
6. Results

Thin acoustic window will become acoustically transparent. If the thickness is less than λ/4, the reverberation levels reduces significantly (Figure 8a). At large thicknesses, the multiples do not interfere but are detected individually. The periodicity of the reverberation depends on $^{d}/_{C}$. The amplitude of these multiples can only be adapted by changing the acoustic impedance and thus the mechanical properties of the acoustic window. These multiples will negatively influence the reliability of the thickness measurement [1].

The reflected signal from a tilted acoustic window will not arrive simultaneously (Figure 9b). At proper orientations, these phase differences will interfere destructively and result in a reduced distortion level (Figure 8b). However, wave conversion inside the acoustic window will occur because the incoming wavefield is not perpendicular to the direction of the propagating wave. Together with the standing wave inside the acoustic window the wave conversion will become a dominant distortion for angles larger than 6 degrees (Figure 9b and Figure 10b). A tilted acoustic window is therefore only advantageous at small angles.

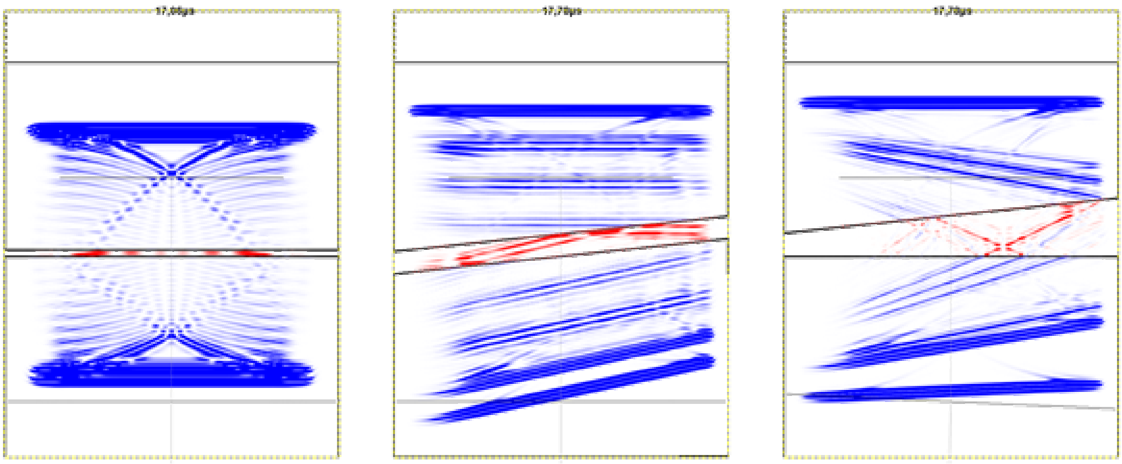
The angle between the transducer surface and the internal surface of the wedge shaped window is much smaller compared to the tilted window. The transducer angle is adopted such that the reflected signal from the steel reflector arrives in phase at the transducer angle. This reduces the amplitude of the converted waves and remains the amplitude of the reflected signal from the steel reflector (Figure 8c). Due to the shape of the wedge, the resonator has variable dimensions and thus the standing wave pattern varies along the lateral position of the wedge (Figure 9c).

A wedge shaped window improves the performance of the system. The distortion due to a wedge shaped acoustic window significantly reduces at wedge angles between 2 and 5 degrees (Figure 10c).



a) b) c)

Figure 8 Typical logarithmically scaled responses for an acoustic window with a thickness of 0.6 mm (a), a tilted window at 6 degrees (b) and wedge shaped window at 6 degrees (c).



a) b) c)

Figure 9 Typical snapshots for an acoustic window with a thickness of 0.6 mm (a), a tilted window at 6 degrees (b) and wedge shaped window at 6 degrees (c).

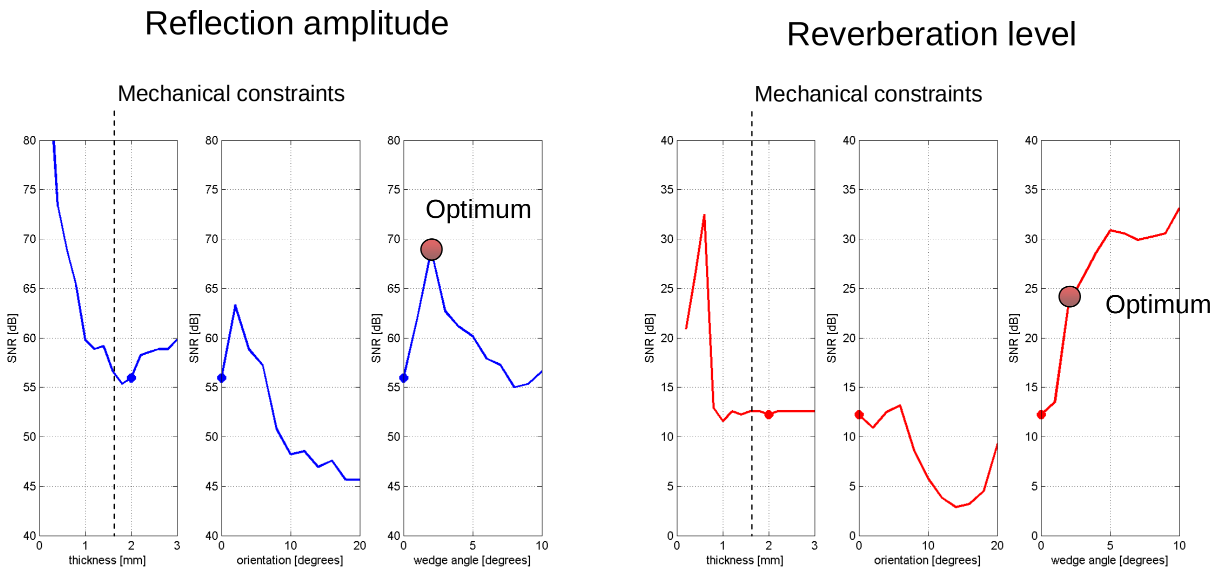


Figure 10 Results for the shot generated noise level (a) and reverberation level (b). as function of thickness, tilt and wedge angle of the acoustic window. The standard configuration is denoted by the dot.

7. Conclusions

Due to mechanical constraints, a standard acoustic window in an ultrasonic bore-hole scanner shows distortion of the measured signals. The distortion results in a reflection signal from the acoustic window and reverberation inside the acoustic window. Proper design is essential to reduce this distortion.

By numerical modeling with UMASIS responses can be simulated under various conditions. These responses provide accurate information about the severity of the distortion. The snapshots enable us to pinpoint the causes of reflection.

Parameter ranging provides good insight in improvement directions. The parameters varied in this study are thickness, orientation and shape of the acoustic window. The result showed that a proper shape of the acoustic window significantly reduced the distortion of the acoustic window.

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