Target echo strength of layered media with an active surface

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Abstract: *Layered media, in form of both fluid layers and solid structures, play an important role in underwater acoustics. They occur as sonar windows, sonar reflectors, anechoic coatings, tank-linings or underwater structures and vehicles. However, the acoustically either desired total absorption, total reflection or total transmission is not achieved in practice. The acoustic behaviour of the layers play a particularly important role in the resulting target echo strength of an object. Active surfaces, for example made of piezo-ceramics, increase the possibilities of influencing the target echo strength beyond the geometry, material properties and material composition of the passive layers. This study compares the target strength behaviour of different layered media including active surfaces for underwater application. An analytical model is used to investigate the vibro-acoustic behaviour of the solid structures, the influence of the active surface and the resulting reflection and transmission behaviour. When the reflection of a surface is minimized by a single active layer, the transmission is not minimized and in some cases even increased. This is a particular problem in layered media, as the transmitted sound waves can cause subsequent layers and structures to vibrate and thus increase the total target echo strength. Various countermeasures are being investigated to prevent this.*

Keywords: *layered media, active surface, active layer, piezoelectric layer, reflection, transmission, analytical model, Echo Reduction, Transmission Loss*

1. INTRODUCTION

Layered media in underwater acoustics are often either chosen specifically for acoustic purposes or are unavoidable for other reasons. The layers are often desired to either totally reflect, transmit or absorb an incident acoustic wave (e.g. reflection: sonar reflectors; transmission: sonar-windows; absorption: anechoic coatings or tank linings). However, the total effect is almost never achieved in practical underwater applications, although achieving good reflection or transmission is much easier than preventing it, respectively achieving good absorption. Active surfaces, for example made of piezoceramics, increase the possibilities of influencing the reflection/transmission/absorption characteristics of layered media, and thus increase the possibilities of influencing the resulting Target Strength (TS) beyond the geometry, material properties and material composition of the passive layers. There have been many theoretical and practical approaches on investigating the effect of active surfaces / active coatings towards reflection, beginning with [1] over to [2], and [3], and most recently [4] and [5]. In most cases, the interaction between the incident wave and the active layer is investigated without considering possible other layers behind the active coating, as well as their significance for an optimal actuator and control design, and without considering oblique incidence. In this study, an approach to layered media with an active surface is shown, taking into account oblique sound incidence and its interaction with infinite solid elastic layers. Furthermore, different configurations of layered media behind the active layer and placement of the active layer are investigated. Finally, conclusions are drawn for the ideal configuration of the active layer and the control system to reduce Target Strength in layered media.

2. ACOUSTIC MODELING OF LAYERED MEDIA

A transfer matrix approach is used to model layered media. The systematic of order and numbering of the layers is based on [7] and shown in Figure 1 (a). Each layer i is assigned its specific acoustic properties depending on the material, as shown in Table 1. The transfer matrix model for investigating the influence of up to two active layers on reflection and transmission is adapted from [3] Equation (23). For modeling the elastic layer, different approaches can be found in [6] and the assumptions, simplifications and accuracy limits for the different models of plates and elastic layers are discussed there in detail. In order to get the best accuracy with focus on vibroacoustic, the approach from [6] Equation (27) is selected, which takes into account anti-symmetric as well as symmetric motion. This makes it possible to take a further step away from idealized 1D transmission models and to investigate the influence of possible vibroacoustic effects on the performance of the active layer. For considering oblique sound incidence, the effective proportion of the wavenumber k and of the characteristic Impedance Z_c in normal direction are expressed as function of the incident angle θ_i in each layer i: $k_{eff,i} = cos(\theta_i)k_i = cos(\theta_i)\frac{2\pi f}{c_l}$, $Z_{c,eff,i} = \frac{Z_{c,i}}{cos(\theta_i)} = \frac{\rho_i c_{l,i}}{cos(\theta_i)}$, with the frequency f, longitudinal wave speed $c_{l,i}$ and density ρ_i. θ_i is calculated from Snell's law with $\theta_i k_i = \theta_{i+1} k_{i+1}$.

2.1. CONTROL ERRORS AND TARGET STRENGTH

When considering oblique sound incidence, the influence of the width of the individual piezoelectric actuators must also be taken into account. This is because for oblique sound in-

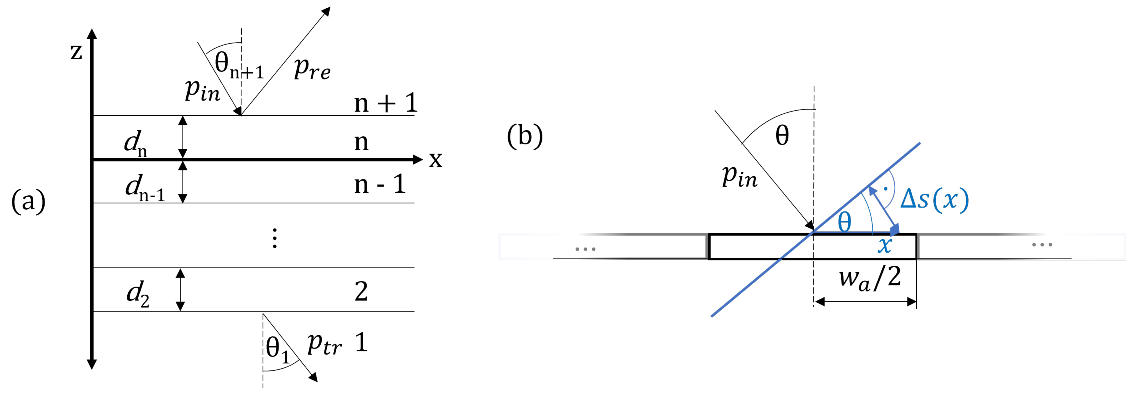

Figure 1: (a) Geometry of layered media, adapted from [7] (b) pressure error of a finite sized piezo strip for oblique incidence

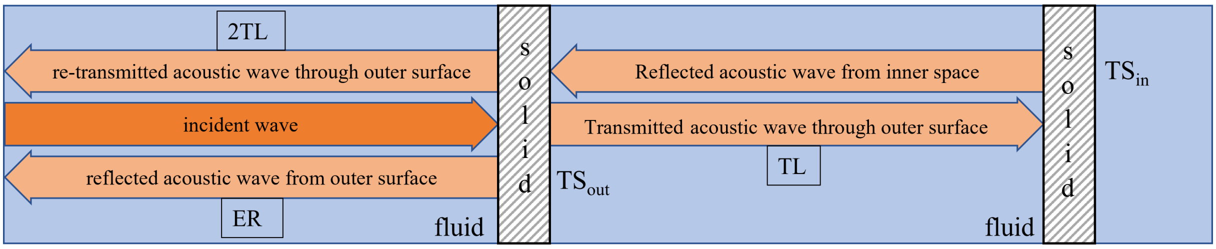

Figure 2: Acoustic waves incident, reflected and transmitted into an underwater structure and ER and TL, adapted from [8]

cidence, only the velocity of an infinitesimally wide part of the actuator corresponds perfectly to the velocity needed for influencing the incident sound wave in the desired way (for example $p_{re} = 0$). The difference between the remaining part of the actuator and the sound wave therefore leads to a deviation from the desired value of the reflection respectively transmission. Therefore, the actuator layer is assumed as finite sized strips with width w_a that are lined up horizontally next to each other, as shown in Figure 1 (b). The error $\epsilon(\theta, w_a) = \frac{\Delta p_{error}}{p_{in} - p_{re,passive}}$ for the control of the reflected and transmitted pressure for a finite sized actuator strip with width w_a under oblique incidence θ can be expressed as:

$$\epsilon(\theta, w_a) = (w_a - \int_{-\frac{w_a}{2}}^{\frac{w_a}{2}} cos(k\Delta s(x))dx)\frac{1}{w_a} = (1 - \frac{2sin(k\frac{w_a}{2}sin\theta)}{k\frac{w_a}{2}sin\theta}) \tag{1}$$

$$|R^*(\theta, w_a)| = |R(\theta)_{active}| + (|R(\theta)_{active]}| - |R(\theta)_{passive}|) \cdot \epsilon(\theta, w_a) \tag{2}$$

$$|T^*(\theta, w_a)| = |T(\theta)_{active}| + (|T(\theta)_{active}| - |T(\theta)_{passiv}|) \cdot \epsilon(\theta, w_a) \tag{3}$$

For objects with an outer and an inner solid layer/structure, the acoustic wave that is transmitted from the outer to the inner structure will excitate the inner structure. This problem is described and modeled in [8] and shown in Figure 2. Emission Reduction (ER) and inner Transmission Loss (TL) can be calculated from R, respectively from T:

$$ER = 10\log|\frac{1}{R^2}|, TL = 10\log|\frac{1}{T^2}| \tag{4}$$

When reducing ER and TL of the outer structure, the total TS can be calculated as seen in [8], Eq. (35):

$$TS_{total} = 10\log(10^{\frac{TS_{out}-ER}{10}} + 10^{\frac{TS_{in}-2TL}{10}}) \tag{5}$$

material properties	**Piezo (P)**	**Steel (S)**	**Water (W)**	**Air (A)**
ρ in $\mathrm{kg/m^3}$	7600	7850	1000	1.2
c_l in $\mathrm{m/s}$	4108	5920	1500	343
g_{33} in $\mathrm{F/m}$	24.535×10^{-3}	-	-	-
e_{33} in $\mathrm{N/(Vm)}$	15.25	-	-	-
E in $\mathrm{N/m^2}$	-	210×10^9	-	-
ν	-	0.3	-	-

Table 1: Material properties

3. MODELING RESULTS

To evaluate the influence of the passive layers on the controled system with one acutator, four different passive layer configurations are selected as Benchmarks. In a second step the influence of the actuator placement and the number of actuators is investigated by using three additional configurations. Figure 3 shows the sequence and dimensions of the layers of each configuration. The material properties used for each layer are listed in Table 1.

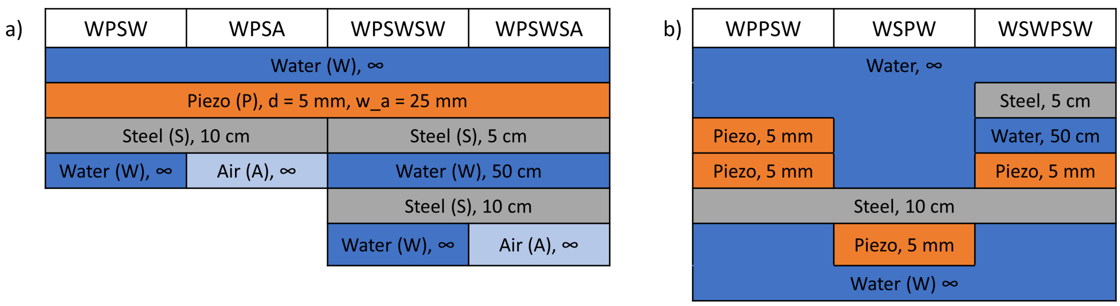

Figure 3: a) Configuration of passive layers with single actuator, b) Configuration of actuator placement and number

3.1. INFLUENCE OF PASSIVE CONFIGURATION

The corrected Echo Reduction ER* is shown for $0.1\,\mathrm{kHz} \leq f \leq 20\,\mathrm{kHz}$ and $0° \leq \theta_{n+1} \leq 85°$ in Figure 4.

There are two main acoustic effects that can be clearly identified especially for passive condition: The coincidence frequency for configurations WPSW and WPSA, as well as the $\lambda/2$ waveguide effect of the $0.5\,\mathrm{m}$ thick water layer for WPSWSA and WPSWSW. The results for active control are shown within the same limits as in the passive case, but related to the Helmholtz number $k \cdot w_a/2$ instead of the frequency, as the error ϵ directly depends on the actuator width w_a. The displayed results are calculated for $w_a = 0.05\,\mathrm{m}$. As the acoustic effects on ER^* can still be seen with control on, the influence of the angle θ and $k \cdot w_a/2$ can be seen in

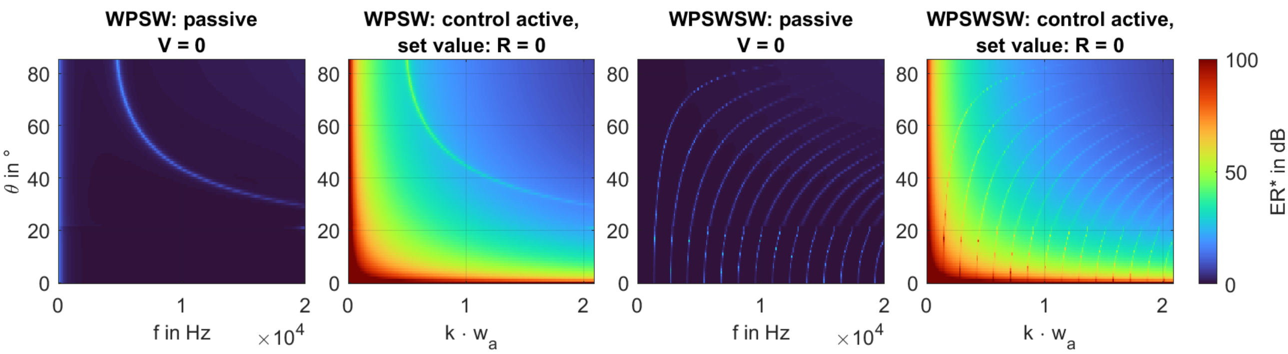

Figure 4: Comparison of acoustic effects of one and two steel layers (WPSW, WPSWSW) with control off and control on.

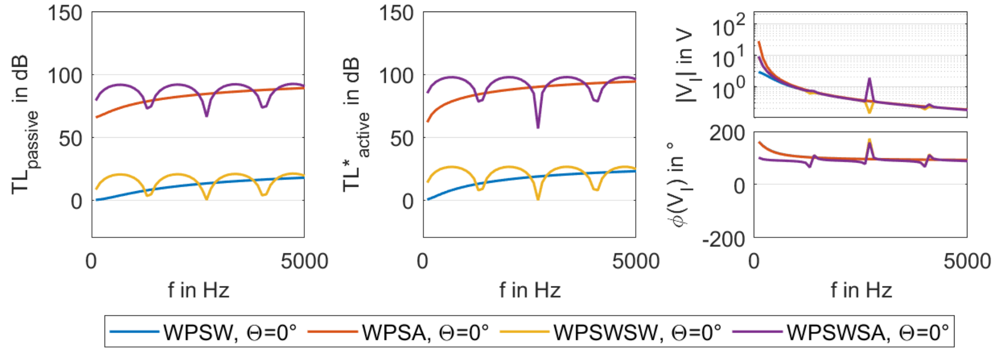

Figure 5: TL in active and passive mode and V_I for layer WPSW, WPSA, WPSWSW and WP-SWSA.

the picture. As the Echo Reduction for most of the frequency band is 0 dB without control, the minimum gain in ER^* with active control is about 10 dB for the most unfavorable constellation of θ and f in the shown limits. The results for control on are based on the assumption of ideal linear actuator behavior and an ideal control system, in particular the performance and linearity limits of the actuator are not taken into account here, but the interaction of those limits with the overall reduction performance could be easily implemented in the future if the corresponding data is available.

Because active control is usually used in the lower frequency band, the upper frequency limit is decreased to 5 kHz. As Figure 4 already shows the dependency of acoustic effects from θ, for further comparison of the first four configurations, only values for $\theta = 0°$ will be shown. Comparing TL in passive and active condition as well as Voltage V_I in Figure 5, the $\lambda/2$ waveguide effects can be seen as well as the nearly soundhard boundary delivered by air. The interesting aspect is, that for active control the average of TL slightly increases in all configurations, but some local minima further decrease, which leads to more acoustic energy reaching the bottom layer. As the minima of TL WPSWSW and WPSWSA can also be observed as a peak in the Voltage, obviously more electric energy is needed to compensate the waveguide effect and thus leads to increased Transmission. Summing up the findings from the results shown in this plot, a single active layer on top of a multilayer configuration that controls ER will not lead to reduced TL. For system consisting of outer and inner structures, especially in the lower frequency range there is still much acoustic energy getting to the inner structure with its own acoustic response TS_{in}.

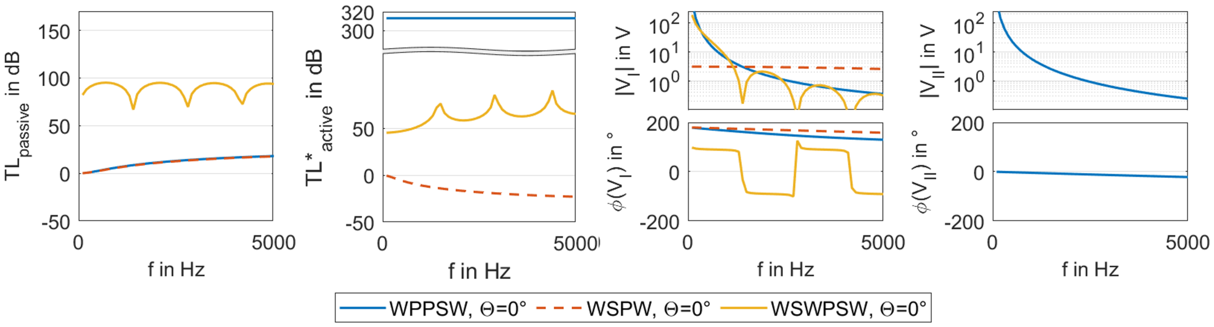

Figure 6: Influence of actuator placement and number (configurations from Figure 3 b))

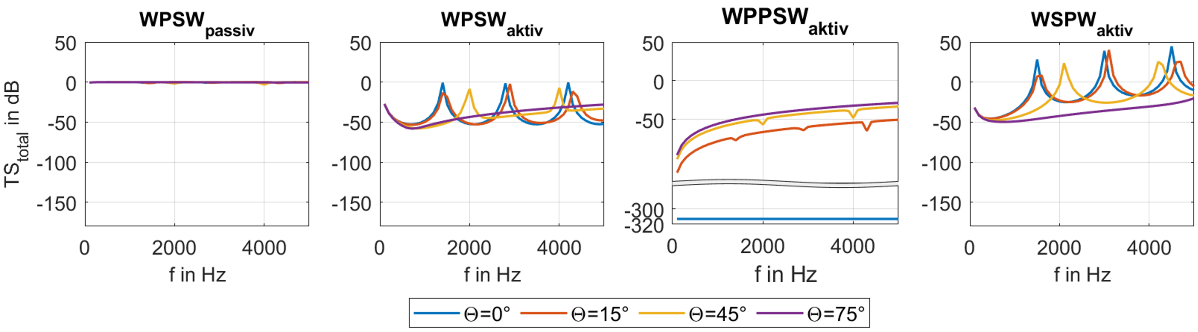

Figure 7: Comparison of TS_{total} for WPSW, WPPSW and WSPW with $TS_{out} = TS_{in} = 0\,$dB

3.2. INFLUENCE OF ACTUATOR PLACEMENT AND NUMBER

For increasing TL, different measures are investigated by changing actuator placement and number, as shown in in Fig. 3 (b): First, using a double-layer actor, with the second layer being controlled for T=0 (WPPSW). Second, shifting the single active layer to another position inside the layered media (WSPW and WSWPSW). The results are shown in Figure 6. The results of TL^*_{active} show a very strong increase for the dual layer, while for the single layer with different positions it clearly decreases in comparison to the passive mode. The strong performance of the dual layer regarding TL comes at the cost of a much higher voltage (for each active layer) especially for $f < 2000\,$Hz.

3.3. IMPACT ON TARGET STRENGTH

The impact of the resulting ER and TL on the total TS of a multilayer object can be evaluated using Eq. 5. Therefore, TS_{in} and TS_{out} are set to arbitrary fixed values, for simple evaluation and comparison 0 dB is chosen for both, and ER and TL are chosen from WPSW, WPPSW and WSPW as these configurations represent the outer layer. The results are shown in Figure 7. The passive layer with ER ≈TL≈ 0 dB shows a TS_{total} of nearly 0 dB, while the layer with the dual actuator shows the lowest TS, especially for normal incidence. WPSW in active mode shows an overall reduction of TS_{total}, in contrast configuration WSPW at the frequencies near the $\lambda/2$ waveguide effect target strength is increased, possibly by energy from the active system being added to the incidend acoustic energy.

4. CONCLUSION

In this study, an extended analytical approach for calculating transmission and reflection of layered media with an active coating has been used to investigate different layer configurations. For coincidence- and waveguide effects a clear influence on the frequency response of the required control voltage is determined. A single active layer can only be used to control either transmission or reflection, but not both at the same time. Because of that, for example the transmission of an incident wave will not be suppressed when actively reducing reflection and in some cases even increased. This leads to the question which measures can be found to reduce transmission and reflection at the same time. Therefore different positions of the actuator layer have been investigated and their effect on the total TS has been evaluated. The dual layer actuator shows by far the best results especially for $f < 2000\,\mathrm{Hz}$ and also with oblique incidence up to $85°$, although it needs much higher voltages compared to other configurations that were evaluated. The sometimes heavy phaseshifts and amplitude peaks of the ideal control voltage and with the necessary control voltages for low frequencies ask for a robust, adaptive system with low-frequency-optimized actuators to successfully increase ER or TL of plane, multilayered objects for oblique incidence.

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