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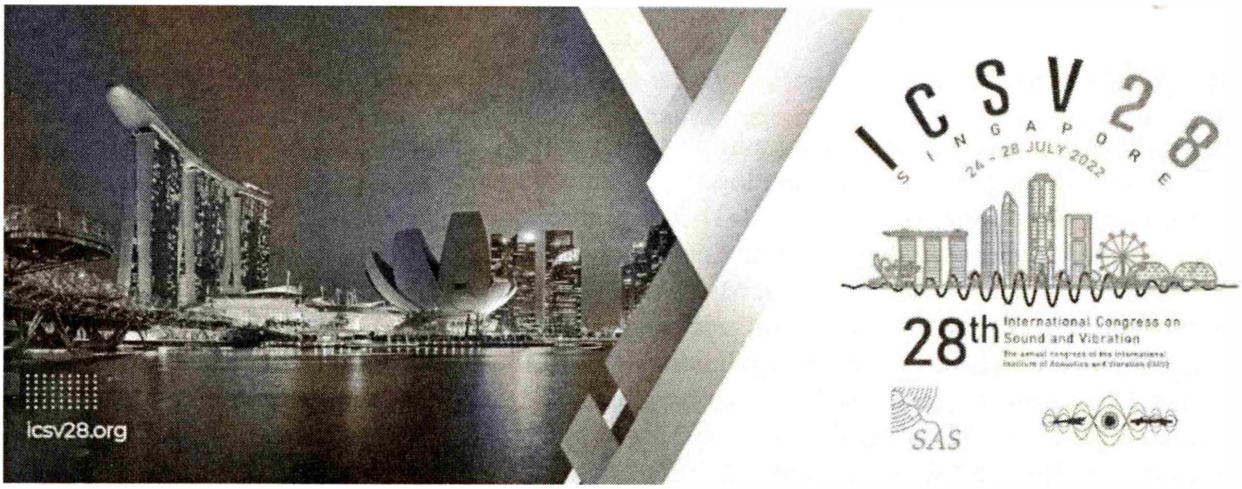
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UNDERWATER SOUND PROPAGATION THROUGH AN AIR-BUBBLE MEDIUM IN AN ACOUSTO-ELASTIC WAVEGUIDE

H.Özkan Sertlek

Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
e-mail: H.O.Sertlek@tudelft.nl

Apostolos Tsouvalas

Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
e-mail: A.Tsouvalas@tudelft.nl

The offshore human activities create a risk for the marine environment and influence the communications, hearing, behaviour and prey-predator relations of the marine animals. The air-bubble curtains are one of the noise mitigation techniques widely used by the offshore industry to minimize these adverse effects of underwater sound. The simulations of the underwater sound propagation and sound source properties could provide practical information in the design phase of the offshore activities as a complementary tool to sound measurements. This paper develops a coupled mode theory-based solution to model sound propagation through air-bubble curtains, including backscattering effects. The bubbly medium is assumed to occupy a vertical column in the seawater and is described by effective medium parameters, which are considered accurate for the frequency range of interest. The continuity of pressure, velocity, displacements, and stresses are considered at the vertical boundaries defining the domain in which the air-bubble cloud is released. Subsequently, the mode-coupling matrices are derived using the orthogonality of the acousto-elastic modes. Numerical challenges are discussed pertaining to the implementation of this solution method. The results are analyzed for various acoustic sources to investigate the air-bubble medium performance in different system configurations.

Keywords: underwater acoustic, noise mitigation, normal modes, coupled mode

1. Introduction

Offshore human activities such as shipping, seismic surveys, explosions and offshore pile-driving can cause temporary or permanent hearing loss for marine animals and affect their behaviour communications, and prey-predator relationships [1-3]. The anthropogenic underwater noise and its contribution to underwater soundscape depend on the environmental properties temporal, spatial and spectral distribution of sound source properties [4]. Many countries introduce underwater noise regulations for specific types of sound sources (such as seismic airguns and pile-driving) to avoid adverse impacts of underwater sound on marine life. These regulations define a threshold in a relevant metric in a specific distance for the hearing ranges of specific marine animals [5-7]. The underwater noise mitigation approaches have been applied during the offshore human activities to reduce the sound levels to satisfy the noise criteria. The air-bubble curtains are one of the most common and efficient noise mitigation techniques [8]. The mathematical modelling techniques for the sound sources [9,10], propagation [11] and mitigation [12] can be used as a practical prediction tool for the expected noise levels and performance of the air-bubble curtains. These mathematical tools can be used for different sources. The air-bubble curtain was modelled to mitigate sound from the seismic airgun arrays [13]. The noise mitigation in the pile-driving activities has been modelled, including the near-field sound characteristics, by Tsouvalas and Metrikine [14]. Recently, Peng et al. [12] analyzed the sound escape through the sediment layers below the air-bubble curtains based on the effective-medium approach, including realistic bubble cloud distributions [15].

To include total scattering and transmission properties, the range-dependent sound properties through the bubble curtains, including the continuity and coupling mechanisms between water and bubble layers, should be considered. The coupled normal mode method is one of the well-known acoustic propagation methods for range-dependent problems in underwater acoustics, provided that the discontinuities along the range are stepwise [16-19]. The classical application of the mode coupling approach which is developed for the fluid seabed based on the radial continuity of the acoustic pressure and radial velocity, can provide a realistic solution for many applications such as propagation over seamounts reverberation or propagation loss calculations [20,21]. Some applications of the mode coupling for the elastic waveguides [22,23] investigate the propagation of the surface waves over irregular structures and the transition between isotropic elastic layers [24]. Galanenko [25] proposed a derivation of elastic coupled-mode theory in curvilinear orthogonal coordinates for slowly varying medium parameters.

For the noise mitigation problems encountered in seismic surveys and pile driving, the largest amount of acoustic energy is released at frequencies below 400-500 Hz. Low-frequency acoustic waves penetrate and interact with multi-layered sediments. When detailed computations of the acoustic insertion loss of air-bubble curtain systems are required, the fluid sediment approximations can give inaccurate results. The sound sources which are directly interacted with the sediments also needs attention. For instance, the pile driving acoustic sources are positioned mainly in the seabed, and the neglection of the elastic nature of the sediments may give erroneous predictions. The noise levels resulting from pile driving are higher close to the seabed, especially in pile vicinity due to the existence of Scholte waves which cannot be captured by the fluidized seabed description.

This work aims to derive a coupled normal mode due to the presence of the air-bubble curtain in an acousto-elastic waveguide. As a general derivation, the point sources are used. However, the approach can be improved for the dipole and line sources as an application of seismic airguns and pile driving. The classical coupled-mode approach handles the continuity of the pressure and velocity in the water and air-bubble layer [17]. Additionally, the continuity of stress and displacement vectors in the sediment is considered in detail. The alternative form of the orthogonality condition for the acousto-elastic waveguides is applied to derive the mode coupling coefficients of back- and forward-propagating wave fields. An analytical solution of the coupled-mode equation system is proposed for single and multiple

bubble curtains. The bubble medium is modelled with a uniform effective sound speed, ignoring its depth dependency for the sake of simplicity. This paper focuses on providing the fundamental mathematical derivations to the sound propagation problems that involve water-bubble and bubble-water interfaces.

2. Normal mode method

The normal mode method can be used for the acousto-elastic waveguides [26]. For monochromatic sources with the time dependency of $e^{i\omega t}$, the wave propagation can be described with the Helmholtz equation by introducing three scalar potentials functions as [27]

$$\nabla^2\phi_f(r,z) + \frac{\omega^2}{c_f^2}\phi_f(r,z) = 0 \tag{1}$$

$$\nabla^2\phi_s(r,z) + \frac{\omega^2}{c_L^2}\phi_s(r,z) = 0 \tag{2}$$

$$\nabla^2\psi_f(r,z) + \frac{\omega^2}{c_T^2}\psi_s(r,z) = 0 \tag{3}$$

in which $\phi_f(r,z,t)$ is the velocity potential in the fluid layer, $\phi_s(r,z,t)$ and $\psi_s(r,z,t)$ are the scalar potentials in the sediment layer, c_L and c_T are the compressional and shear waves related to the complex Lame constants as $c_L^2 = \frac{\lambda+\mu}{\rho_s}$ and $c_T^2 = \frac{\mu}{\rho_s}$. The general solutions to these equation, which satisfy the radiation conditions at infinite radial distance from the source, can be sought for as follows:

$$\phi_f(r,z) = H_0^{(2)}(k_r r)\left(A_1 e^{-k_{z,f}z} + A_2 e^{k_{z,f}z}\right) \tag{4}$$

$$\phi_s(r,z) = H_0^{(2)}(k_r r)(A_3 e^{-\alpha_s z} + A_4 e^{\alpha_s z}) \tag{5}$$

$$\psi_s(r,z) = H_1^{(2)}(k_r r)\left(A_5 e^{-\beta_s z} + A_6 e^{\beta_s z}\right) \tag{6}$$

in which $k_{z,f}$ is the vertical wavenumber in the fluid domain, α_s and β_s are the vertical wavenumbers in the soil domain, and k_r is the horizontal wavenumber satisfying the relation of $k_{r,f}^2 + k_{z,f}^2 = \frac{\omega^2}{c_f^2}$. A_1, A_2, A_3, A_4, A_5 and A_6 are complex-valued constants. The pressure, radial and vertical velocities read as

$$p(r,z) = -i\omega\rho_f\phi_f(r,z) \tag{7}$$

$$v_r(r,z) = \frac{\partial\phi_f(r,z)}{\partial r} \tag{8}$$

$$v_z(r,z) = \frac{\partial\phi_z(r,z)}{\partial z} \tag{9}$$

The displacement-potential and stress-displacements relations read as follows:

$$u(r,z) = \frac{\partial\phi_s(r,z)}{\partial r} - \frac{\partial\psi_s(r,z)}{\partial z} \tag{10}$$

$$w(r,z) = \frac{\partial\phi_s(r,z)}{\partial z} + \frac{1}{r}\frac{\partial(r\psi_s(r,z))}{\partial r} \tag{11}$$

$$\sigma_{rr}(r,z) = (\lambda+2\mu)\frac{\partial u(r,z)}{\partial r} + \lambda\frac{u(r,z)}{r} + \lambda\frac{\partial w(r,z)}{\partial z} \tag{12}$$

$$\sigma_{zr}(r,z) = \mu\left(\frac{\partial u(r,z)}{\partial z} + \frac{\partial w(r,z)}{\partial r}\right) \tag{13}$$

2.1 Coupled mode solution

Different methods can be used to compute the underwater acoustic propagation in range dependent waveguides. Their performance and accuracy depend on the model-specific parameters at different bathymetry types and frequencies [11]. Coupled normal mode theory is one of the accurate modelling methods for the range-dependent waveguides provided that variations in the properties with range can be expressed in a stepwise manner. According to the coupled-mode theory, the range-dependent waveguide is divided into the range independent vertical segments as described by [18]. This approach is widely used in underwater acoustic propagation modelling for range-dependent bathymetry [17]. The geometry of the problem is described in three adjacent vertical segments with the water and bubble-water properties that have a sharp contrast in the properties of the seawater and bubbly mixture, as shown in Fig. 1.

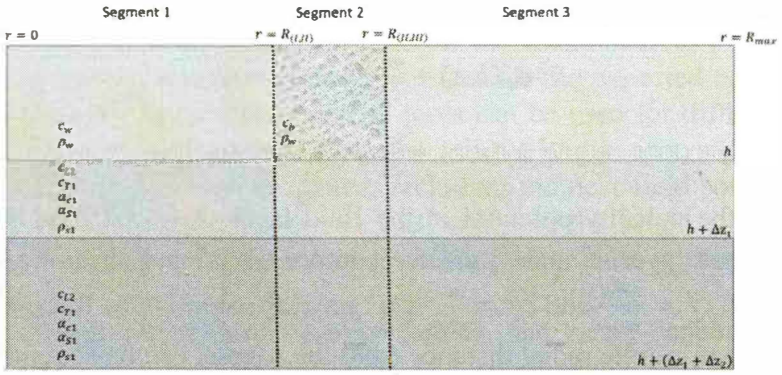


Figure 1: Problem geometry

Based on normal mode theory, the acousto-elastic field quantities can be written as [27] as:

$$p(r,z) = \sum_{m=1}^{M}[a_m H_0^1(k_m r) + b_m H_0^2(k_m r)]\, p_m(z) \tag{14}$$

$$v_r(r,z) = \sum_{m=1}^{M}[a_m H_1^1(k_m r) + b_m H_1^2(k_m r)]\, v_{r,m}(z) \tag{15}$$

with a_m and b_m being the complex-valued mode coefficients in the frequency domain, $H_{0,1}^{1,2}$ is the zeroth (and first) order Hankel functions of the first and second kind while $p_m(z)$ and $v_{r,m}(z)$ represent the vertical eigenfunctions of the pressure and radial velocity, respectively. This form of the equation can be used for the forward-going and back-going wavefields as a modified notation of [27]. Similarly, displacements and stresses can be expressed as follows:

$$u(r,z) = \sum_{m=1}^{M}[a_m H_1^1(k_m r) + b_m H_1^2(k_m r)]\, u_m(z) \tag{16}$$

$$w(r,z) = \sum_{m=1}^{M}[a_m H_0^1(k_m r) + b_m H_0^2(k_m r)]\, w_m(z) \tag{17}$$

$$\sigma_{zr}(r,z) = \sum_{m=1}^{M}\left(a_m H_1^1(k_m r) + b_m\, H_1^2(k_m r)\right)\sigma_{zr,m}(z) \tag{18}$$

$$\sigma_{rr}(r,z) = \sum_{m=1}^{M} a_m\left[\sigma_{rr}^{H_0}(z) + \frac{\sigma_{rr}^{H_1}(z)}{r}\frac{H_1^1(k_m r)}{H_0^1(k_m r)}\right]H_0^1(k_m r) + b_m\left[\sigma_{rr}^{H_0}(z) + \frac{\sigma_{rr}^{H_1}(z)}{r}\frac{H_1^2(k_m r)}{H_0^2(k_m r)}\right]H_0^2(k_m r) \tag{19}$$

in which $\sigma_{zr,m}(z) = \mu\left(\frac{\partial u_m(z)}{\partial z} - k_m w_m(z)\right)$.

The sound pressure, displacement and stress must be continuous at the boundaries between different vertical segments. The range between the first and second vertical segments is represented by $R_{(I,II)}$. The pressure and radial velocity must be continuous at the vertical transition range ($R_{(I,II)}$) in the water layer, i.e.:

$$p^{(I)}(R_{(I,II)}, z) = p^{(II)}(R_{(I,II)}, z) \tag{20}$$

$$v_r^{(I)}(R_{(I,II)},z) = v_r^{(II)}(R_{(I,II)},z) \tag{21}$$

In the elastic domain, the displacements and stresses must be continuous at vertical transition zones:

$$u^{(I)}(R_{(I,II)},z) = u^{(II)}(R_{(I,II)},z) \tag{22}$$

$$w^{(I)}(R_{(I,II)},z) = w^{(II)}(R_{(I,II)},z) \tag{23}$$

$$\sigma_{zr}^{(I)}(R_{(I,II)},z) = \sigma_{zr}^{(II)}(R_{(I,II)},z) \tag{24}$$

$$\sigma_{rr}^{(I)}(R_{(I,II)},z) = \sigma_{rr}^{(II)}(R_{(I,II)},z) \tag{25}$$

The eigenfunctions are related to each other with the orthogonality:

$$-\int_0^h \frac{1}{i\omega k_q} p_p v_{r,q}\, dz + \frac{1}{k_q}\int_h^{h+H}\left(\sigma_{rr,p}^{H_0} u_q - w_p \sigma_{zr,q}\right)dz = \delta_{pq} \tag{26}$$

Various forms of the orthogonality relation can be found [28-31] in the literature. Next, the orthogonality condition can be used to eliminate the non-orthogonal term in the mode sum in the right segment. After a set of mathematical operations based on the continuity and orthogonality conditions, the coupling matrix for the transition between the first and second segments can be written as

$$\begin{bmatrix} H_0^1(k_q^{(II)}R_{(I,II)}) & H_0^2(k_q^{(II)}R_{(I,II)}) \\ H_1^1(k_q^{(II)}R_{(I,II)}) & H_1^2(k_q^{(II)}R_{(I,II)}) \end{bmatrix}\begin{bmatrix} a^{(II)} \\ b^{(II)} \end{bmatrix} = \begin{bmatrix} D_{1mq}H_0^1(k_m^{(I)}R_{(I,II)}) + D_{2mq}H_1^1(k_m^{(I)}R_{(I,II)}) & D_{1mq}H_0^2(k_m^{(I)}R_{(I,II)}) + D_{2mq}H_1^2(k_m^{(I)}R_{(I,II)}) \\ C_{mq}H_1^1(k_m^{(I)}R_{(I,II)}) & C_{mq}H_1^2(k_m^{(I)}R_{(I,II)}) \end{bmatrix}\begin{bmatrix} a^{(I)} \\ b^{(I)} \end{bmatrix} \tag{27}$$

where C_{mq}, D_{1mq} and D_{2mq} are the coupling coefficient that are calculated based on the orthogonality condition. A similar transition matrix can be obtained for the transitions between the second and third segments by simply replacing the eigenfunctions and eigenvalues of the relevant segments.

3. Results

Sound propagation over a single homogenous bubble curtain has been considered as a first implementation step of the proposed method. The water depth assumed is 25 m. The distance between the bubble curtain and point sound source is 70 m. The thickness of the bubble curtain is assumed as 3 m. The sound speed in the water is 1500 m/s. The effective sound speed in the air-bubble curtain segment is 250 m/s. The marine sediment consists of two layers. The frequency chosen for the analysis is set to 250 Hz. The detailed sediment properties are given in Table 1.

Table 1: Sediment properties

	Marine sediment	Bottom soil
thickness	5 m	25 m
$c_L\ [m/s]$	1600	1850
$c_T\ [m/s]$	84	360
$\rho\ [kg/m^3]$	1620	1940
$\alpha_p\ [dB/\lambda]$	0.91	0.88
$\alpha_s\ [dB/\lambda]$	1.86	2.27

Before calculating entire sound field, the continuity conditions at the vertical interfaces are tested. The amplitudes of pressure, radial velocity, displacements and stress vectors are compared at the interfaces of air-bubble and water segments in Fig.2.

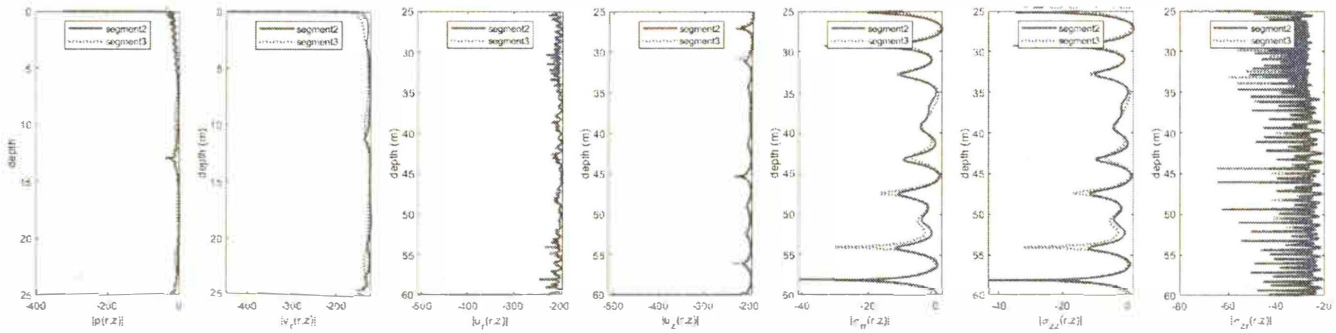


Figure 2: Vertical variation of pressure, radial velocity,displacements and stress vectors at interface of air-bubble and water segments.

The continuity conditions at the water and air-bubble interfaces and water-sediment interfaces are satisfied. The acousto-elastic sound field (i.e. the pressure in the water layer and the σ_{zz} stress component of the stress field) with and without air-bubble curtain is shown in Fig. 3.

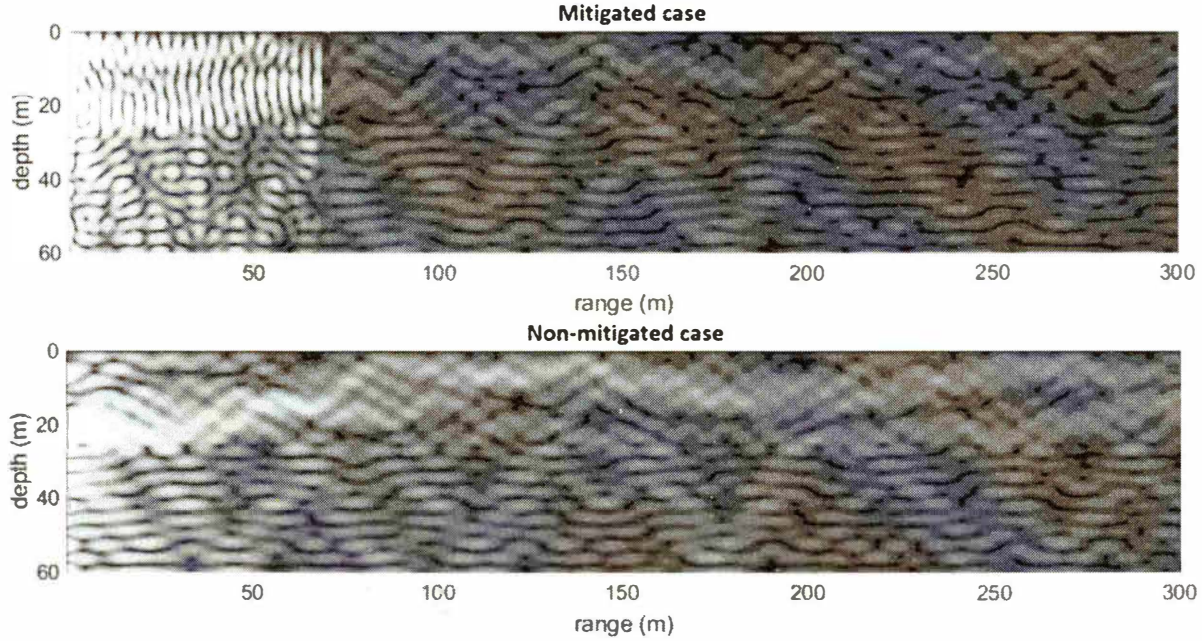


Figure 3: Sound pressure in water layer (0 m to 25 m) and stress in the sediment layer (25 m to 50 m). The upper figure contains an air-bubble curtain at 70 m. The lower figure shows the unmitigated field without air-bubble curtain. The frequency is 250 Hz.

As can be seen, the interference pattern of the sound field is affected, due to the strong back-reflections from the air-bubble curtain, up to 70 m. The sound field in the water layer is attenuated after 70 m since most of the acoustic energy is not transmitted through the air-bubble curtain. The differences in the acoustic interference of the elastic sediment layer is also noticeable in the presence of the air-bubble curtain.

4. Conclusions

The paper establishes a fully-coupled normal mode solution considering the continuity of pressure, velocity, displacement, and stress for the acousto-elastic waveguides. Although the results discussed in this work refer to three vertical layers, the derivations can be extended to multiple segments that can

include the radial gradient of the sound speed from the water layer to the effective medium of the air-bubble medium. During the implementation of the method, some numerical challenges have been encountered due to the large condition number of the matrices and complex arguments of the Hankel functions. Therefore, the convergence and stability tests of the numerical solutions are required, especially for higher frequencies involving a larger number of complex eigenvalues. In future works, the proposed mathematical solution will be used to parametrically study the impact of effective sound speed, sediment type, air-bubble curtain positioning on the noise mitigation potential.

REFERENCES

Dähne, M., Tougaard, J., Carstensen, J., Rose, A., abe-Nielsen J., Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises, *Mar Ecol Prog Ser.* 580: 221–237 (2017).

2 Finneran J.J., Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015,*J. Acoust. Soc. Am.*, 138: 1702, (2015).

3 Duarte C. M. , Chapuis L.,Collin S. P. , Costa D. P., Devassy R. P., Eguiluz V. M., Erbe C. , Gordon T. A. C., Halpern B. S., Harding H. R. , Havlik M. N. , Meekan M., Merchant N. D. , Miksis-Olds J. L. , Parsons M., Predragovic M. , Radford A. N. Radford C. A. Simpson S. D. Slabbekoorn H., Staaterman E. , Van Opzeeland I. C. Winderen J., Zhang X. , Juanes F., The soundscape of the Anthropocene ocean, *SCIENCE*, Vol. 371, No. 6529 , (2021).

4 Sertlek H.Ö., Ainslie M.A., Slabbekoorn H., ten Cate C.J., Source-specific sound mapping: spatial, temporal and spectral distribution of sound in the Dutch North Sea, *Environmental Pollution*, 247, Pages 1143-1157, (2019).

5 National Marine Fisheries Service (NPL), Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., OAA. *NOAA Technical Memorandum NMFS-OPR-55*, 178, (2016).

6 National Marine Fisheries Service, Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. *NOAA Technical Memorandum NMFS-OPR-59,* (2018).

7 Southall B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Elli on, W.T., Nowacek, D.P., Tyack P.L. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals*, 45(2): 125-232, (2019).

8 Bellmann M.A., Brinkmann J., May A., Wendt T., Gerlach S.,Remmers P.,Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. Edited by the ITAP GmbH, (2020).

9 Sertlek H. Ö., Blacquière G., Effects of the Rough Sea Surface on the Signature of a Single Air Gun, *IEEE Journal of Ocean Engineering*, (99):1-7, (2019).

10 Tsouvalas, A., Underwater noise generated by offshore pile driving, PhD Thesis, Delft University of Technology, The Netherlands, (2015).

11 Sertlek H.Ö., Ainslie M.A., Heaney K., Analytical and Numerical Propagation Loss Predictions for Gradually Range-Dependent Isospeed Waveguides, *IEEE Journal of Ocean Engineering*, (2018).

12 Peng Y.; Tsouvalas, A.; Stampoultzoglou, T.; Metrikine, A. Study of the Sound Escape with the Use of an Air Bubble Curtain in Offshore Pile Driving. *J. Mar. Sci. Eng.*, 9, 232, (2021).

13 Wehner, D.; Landrø, M. The impact of bubble curtains on seismic air-gun signatures and its high-frequency emission. *Geophysics*, 85, P1–P11, (2020).

14 Tsouvalas, A.; Metrikine, 2016, A. Noise reduction by the application of an air bubble curtain in offshore pile driving. *J. Sound Vib.*, 371, 150–170. (2015).

15 Bohne T.; Griessmann, T.; Rolfes, R. Modeling the noise mitigation of a bubble curtain. *J. Acoust. Soc. Am.*, 146, 2212–2223,(2019).

16 Pierce, A. D., Extension of the method of normal modes to sound propagation in an almost-stratified medium, *J. Acoust. Soc. Am.* 37, 19-27,(1965).

17 Jensen F.B Kuperman W.A, Porter M.B.,Schmidt H., *Computational Ocean Acoustics*, AIP, New York, (2011).

18 Evans, R. B., A coupled mode solution for acoustic propagation in a waveguide with stepwise depth variations of a penetrable bottom, *J. Acoust.Soc. Am.*, 74, 188-195,(1983).

19 Evans R.B., Gilbert K.E, Acoustic propagation in a refracting ocean waveguide with an irregular interface,*Computers & Mathematics with Applications*,Volume 11, Issues 7–8 ,Pages 795-805,(1985).

20 Luo W. and Schimidt H., Three-dimensional propagation and scattering around a conical seamount, *J. Acoust. Soc. Am.* 125, 52, (2009).

21 Fawcett J.A., A derivation of the differential equations of coupled mode propagation, *J. Acoust. Soc. Am.* 92, 290–295, (1992).

22 Tromp J., A coupled local-mode analysis of surface-wave propagation in a laterally heterogeneous waveguide, *Geophysical Journal International*, Volume 117 Issue 1, Pages 153–161, (1984).

23 Maupin Surface waves across 2-D structures: A method based on coupled local modes,*Geophysics*., 33, 173–185, (1988).

24 van Dalen K.N., Tsouvalas A., Metrikine A.V.,Hoving J.S.,Transition radiation excited by a surface load that moves over the interface of two elastic layers, *International Journal of Solids and Structures*,Volumes 73–74 ,99-112, (2015).

25 Galanenko V.B., On coupled modes theory of two-dimensional wave motion in elastic waveguides with slowly varying parameters in curvilinear orthogonal coordinates, *J. Acoust. Soc. Am.*,103, 1752 (1998).

26 Westwood E.K., Tindle C.T., Chapman N.R., A normal mode model for acousto-elastic ocean environments, *J. Acoust. Soc. Am.*, 100, 3631–3645, (1996).

27 Tsouvalas and Metrikine, A three-dimensional vibroacoustic model for the prediction of underwater noise from offshore pile driving, *J. Sound Vib.*, 333(8), 2283–2311,(2014).

28 Aki K. and Richards P.G.,*Quantitative seismology: Theory and methods* pp. 286–319, ed., Freeman W.H. San Francisco CA, (1980).

29 Bostock M.G., On the orthogonality of surface wave eigenfunctions in cylindrical coordinates, *Geophysical Journal International*, 103, 763–767, (1990).

30 Herrera I., On a method to obtain a Green's function for a multi-layered half space, *Bulletin of Seismological Society of America*, 54,1087–1096, (1964).

31 Stange S.,Friederich W., Guided wave propagation across sharp lateral heterogeneities: the complete wavefield at a cylindrical inclusion, *Geophysical Journal International*, 11, 470–482, (1992).