6th INTERNATIONAL SCIENTIFIC CONFERENCE

OTEH 2014

ON DEFENSIVE TECHNOLOGIES

PROCEEDINGS

Belgrade, 09 – 10 October 2014

Publisher
The Military Technical Institute
Ratka Resanovića 1, 11030 Belgrade

Publisher's Representative
Doc. Col **Zoran Rajić,** PhD (Eng)

Editor
Zoran Anastasijević, PhD (Eng)

Technical Editing
Dragan Knežević
Liljana Kojičin

Graphic Editing
Milica Dimitrijevic

Printing
300 copies

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

623.4/.7(082)(0.034.2)
66.017/.018:623(082)(0.034.2)

INTERNATIONAL Scientific Conference on Defensive Technologies (6th ; 2014 ; Beograd)
Proceedings [Elektronski izvor] / 6th International Scientific Conference on Defensive Technologies, OTEH 2014, Belgrade, 09-10 October 2014 ; organized by Military Technical Institute, Belgrade ; [editor Zoran Anastasijević]. - Belgrade : The Military Technical Institute, 2014 (Beograd : The Military Technical Institute). - 1 elektronski optički disk (CD-ROM) ; 12 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. - Tiraž 300. - Bibliografija uz svaki rad.

ISBN 978-86-81123-71-3

1. The Military Technical Institut (Belgrade)
a) Војна техника - Зборници b) Технички материјали - Зборници

COBISS.SR-ID 210344204

6th INTERNATIONAL SCIENTIFIC CONFERENCE

ON DEFENSIVE TECHNOLOGIES

SUPPORTED BY

Ministry of Defence

www.mod.gov.rs

Organized by
MILITARY TECHNICAL INSTITUTE
1 Ratka Resanovića St., Belgrade 11000, SERBIA

www.vti.mod.gov.rs

ORGANIZING COMMITTEE

Major General **Bojan Zrnić**, PhD, Chief of the Directorate of Defence Technologies, ***President***

Major General **Dušan Stojanović**, Head of Planning and Development

Major General **Mitar Kovač**, PhD, Head of the Strategic Planning

Major General **Mladen Vuruna**, PhD, Head of the Military Academy, Belgrade

Lieutenant General **Miodrag Jevtić**, PhD, Rector of the University of Defence

Vladimir Bumbaširević, PhD, Rector, University of Belgrade

Aleksandar Gajić, PhD, State Secretary of the Ministry of Education, Science and Technological Development

Milorad Milovančević, PhD, Dean of the Faculty of Mechanical Engineering, Belgrade

Branko Kovačević, PhD, Dean of Faculty of Electrical Engineering in Belgrade

Đorđe Janaćković, PhD, Dean of the Faculty of Technology and Metallurgy, Belgrade

Radomir Milašinović, PhD, Dean of the Faculty of Security Studies, Belgrade

Goran Milošević, PhD, Dean of the Police Academy, Belgrade

Col. **Zoran Rajić**, PhD, Director of the Military Technical Institute, ***Vice President***

Col. **Slobodan Ilić**, PhD, Director of the Technical Test Center, Belgrade

Col. **Stevan Radojčić**, PhD, Chief of the Military Geographical Institute

Nenad Miloradović, JUGOIMPORT - SDPR, Belgrade

Miladin Petković, Director of " Krušik ", Valjevo

Zoran Stefanović, Director of " Sloboda", Čačak

Radoš Milovanović, Director of "Milan Blagojević", Lučani

Dobrosav Andrić, Director of "Prvi Partizan " Užice

Stanoje Biočanin, Director of " Prva Iskra -namenska," Barič

Radomir Gromović, Director of " Zastava oružije", Kragujevac

SECRETARIAT

Danica Simić, MSc, ***secretary***
Marija Samardžić, PhD
Miodrag Ivanišević, MSc
Dragan Knežević,
Suzana Vuković
Liljana Kojičin,

SCIENTIFIC COMMITTEE

Zoran Anastasijević, PhD, Military Technical Institute, *President*
Dragoljub Vujić, PhD, Military Technical Institute, Serbia
Nafiz Alemdaroglu, PhD, Middle East Technical University, Ankara, Turkey
Col. **Zbyšek Korecki**, University of Defence, Brno, Czech Republic
Stevan Berber, PhD, Auckland University, New Zealand
Constantin Rotaru, PhD, Military Technical Academy, Bucharest, Romania
Nenad Dodić, PhD, dSPACE GmbH, Paderborn, Germany
Wang Yuebing, PhD, Laboratory of Acoustics, National Institute of Metrology, Beijing, China
Kamen Iliev, PhD, Bulgarian Academy of Sciences, Center for National Security and Defence, Sofia, Bulgaria
Col. **Stoyan Balabanov**, Ministry of Defence, Defence Institute, Sofia, Bulgaria
Grečihin Leonid Ivanovič, PhD, State College of Aviation, Minsk, Belarus
Brigadier General **Boris Durkech**, PhD, Military Academy, Slovak Republic
Slobodan Stupar, PhD, Deputy Minister of Education, Science and Technological Development
Col. **Goran Dikić**, PhD, University of Defence, Serbia
Col. **Boban Đorović**, PhD, Military Academy, Serbia
Col. **Nenad Dimitrijević**, PhD, Military Academy, Serbia
Col. **Miodrag Regodić**, PhD, Military Academy, Serbia
Lt. Col. **Dragan Trifković**, PhD, Military Academy, Serbia
Vlado Đurković, PhD, Military Academy, Serbia
Biljana Marković, PhD, Faculty of Mechanical Engineering, Sarajevo, Bosnia and Herzegovina
Branko Livada, Luxell Technologies, Toronto, Canada
Col. **Martin Macko**, PhD, University of Defence, Brno, Czech Republic
George Dobre, PhD, University Politehnica of Bucharest, Romania
Momčilo Milinović, PhD, Faculty of Mechanical Engineering, Serbia
Dragutin Debeljković, PhD, Faculty of Mechanical Engineering, Serbia
Slobodan Jaramaz, PhD, Faculty of Mechanical Engineering, Serbia
Bosko Rašuo, PhD, Faculty of Mechanical Engineering, Serbia
Aleksa Zejak, PhD, RT-RK Institute for Computer Based Systems, Novi Sad, Serbia
Strain Posavljak, PhD, Faculty of Mechanical Engineering, Banja Luka, Republic Srpska
Fadil Islamović, PhD, Faculty of Mechanical Engineering, Bihać, Bosnia and Herzegovina
Tomaz Vuherer, PhD, University of Maribor, Slovenia
Silva Dobrić, PhD, Military Medical Academy, Serbia
Zijah Burzić, PhD, Military Technical Institute, Serbia
Lt. Col. **Ivan Pokrajac**, PhD, Military Technical Institute, Serbia
Mirko Kozić, PhD, Military Technical Institute, Serbia
Vencislav Grabulov, PhD, IMS Institute, Belgrade
Lt. Col. **Ljubiša Tomić**, PhD, Technical Test Center, Serbia
Nenko Brkljač, PhD, Technical Test Center, Serbia

OTEH
6th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2014
Belgrade, Serbia, 9 – 10 October 2014

ANALYSIS OF ACOUSTIC CLOAKS FOR ANTI-SONAR CAMOUFLAGE BASED ON LOCAL RESONANCE IN ACOUSTIC METAMATERIALS

KATARINA RADULOVIĆ
IHTM – Center of Microelectronic Technologies, University of Belgrade, Republic of Serbia,
kacar@nanosys.ihtm.bg.ac.rs

ZORAN JAKŠIĆ
IHTM – Center of Microelectronic Technologies, University of Belgrade, Republic of Serbia,
jaksa@nanosys.ihtm.bg.ac.rs

MARKO OBRADOV
IHTM – Center of Microelectronic Technologies, University of Belgrade, Republic of Serbia,
marko.obradov@nanosys.ihtm.bg.ac.rs

DANA VASILJEVIĆ RADOVIĆ
IHTM – Center of Microelectronic Technologies, University of Belgrade, Republic of Serbia,
dana@nanosys.ihtm.bg.ac.rs

Abstract: *Non-visual camouflage plays a significant role in the art of military deception. One of the fields of interest is auditory camouflage, where the goal is to remove the acoustic signature of an object, whether it is generated by the object itself or scattered from a surveillance device like sonar. A recently proposed approach to auditory camouflage is acoustic cloaking, where the object is made 'invisible' in acoustic sense by surrounding it with a cloak of acoustic metamaterial. Acoustic metamaterial is basically an artificial structure tailored to enable control of acoustic wave dispersion through Bragg scattering, where the features of the structure have subwavelength dimensions. The operation of an acoustic cloak is based on negative effective dynamic mass and bulk modulus which can be obtained by local resonances. This leads to a possibility to fully tailor the path of acoustic waves (infrasound, audible waves or ultrasound) around the camouflaged object, effectively enabling one to make waves avoid the object and render it invisible. In this contribution we perform a full finite element modeling of the elements of an acoustic cloak, analyze it and consider coordinate transformation necessary to ensure acoustic concealment of a macroscopic object. We investigated spatial distribution of acoustic waves for two different scatterers, one of them being a cylindrical object with circular basis, another one a cylinder with elliptical basis. All our calculations were performed for a realistic sea water medium, modeled by an empirical formula. We considered the frequency dispersion of the acoustic field in different spectral ranges, from infrasound to audible frequencies. For elliptic cloaks we applied a very simple approach that nevertheless furnished better acoustic cloaking than some more complex layered profiles previously published.*

Keywords: *Acoustic camouflage, Acoustic metamaterials, Phononic crystals, Transformation acoustics, Acoustic cloak.*

1. INTRODUCTION

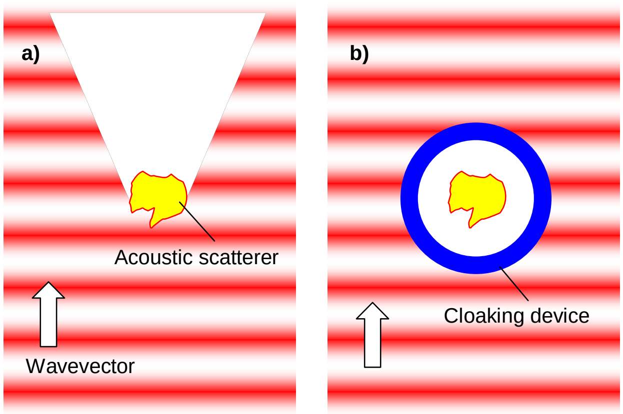
One of the important measures in military camouflage is concealment of military hardware and formations against enemy's observations. A significant position belongs to the concealment against non-visual observation methods, most importantly against radar (microwave electromagnetic range), night vision and heat seeking instruments (infrared range) and sonar (infrasound, audible sound and ultrasound).

Passive and active sonar (acronym for Sound Navigation And Ranging) devices are a means of choice for detection of objects in water. Passive devices simply detect sounds from the environment, created by the target object or reflected or created by some external source and scattered by it. Active devices emit sound pulses and measure their echoes, i.e. they make use of an acoustic transmitter and a receiver. The frequencies of sound used in sonars may vary from low (infrasonic) to very high ultrasonic. Passive measures of camouflage against sonar include the use of noise-generating devices as decoys and the application of sound-absorbent coatings (acoustic stealth) on the surface of the hardware to be concealed.

Probably an ideal stealth approach would be to make acoustic waves avoid the object completely and behave as if nothing were present in their way. It turns out that such kind of concealment is possible in reality. It is called acoustic cloaking and makes use of the recently introduced paradigm, the transformation acoustics [1]. Essentially, transformation acoustics structures basically map the spatial coordinates from one spatial geometry to another and guide a wave along the desired path. Thus an object can be concealed by a transformation optics structure by guiding the acoustic waves in such a way to completely avoid the object, exiting the other side unchanged. It can be said that transformation acoustics is used to "distort" acoustic space in a desired manner [2].

The concept of acoustic cloaking draws its roots from two relatively recent findings in electromagnetics. One of these are the electromagnetic metamaterials, structures with optical properties not readily found in nature [3]. One of the first proposed and fabricated kinds of electromagnetic metamaterials were structures with negative refractive index [4]. Based on electromagnetic metamaterials the transformation optics [5-6] was proposed, where the possibility of arbitrary adjustment of refractive index ensured the possibility to obtain almost any desired spatial distribution of electromagnetic waves. One of the consequences was the proposal of optical cloaks [7] rendering electromagnetic invisibility in a narrow band of the spectrum.

Transformation acoustics [1] was proposed as an obvious extension of transformation optics. It represents mapping of one acoustic space into another with an ultimate result of ensuring full control over sound/ultrasound/infrasound propagation over space and frequency domain. One possible transformation is to "stretch" the acoustic space, thus making the sound waves pass around the object to be concealed without any disturbance. This is an acoustic cloak [8-9], rendering acoustic "invisibility" for an object. A sonar cannot find thus masked object, thus an almost perfect acoustic stealth mode is ensured. The concept of such cloaking is illustrated in Picture 1.



Picture 1: Concept of acoustic cloaking using acoustic metamaterial. a) scatterer disturbs the spatial distribution of acoustic waves; b) acoustic cloak around the scatterer bends waves and removes disturbance, thus ensuring concealment

In order to perform mapping of acoustic space, it was necessary to produce materials with effective mass density and bulk modulus both lower than zero. This has been enabled by utilizing sonic crystals and acoustic metamaterials [10], structures analog to the previously introduced photonic crystals and electromagnetic metamaterials.

Acoustic metamaterials are thus artificial structures with mechanical properties not encountered in nature. An example of acoustic metamaterial is a structure with negative refraction of acoustic waves [11-13], i.e. with a group velocity direction opposite to that of the wave vector. Their characteristic features are subwavelength (much smaller than the operating wavelength) and typically they are built in such a way that local acoustic resonances appear in them. Under certain conditions, these local resonances produce negative effective dynamic mass density and negative bulk modulus [12] – if material is in exact antiresonance with an incident acoustic wave, it will exert force against the wave and thus effectively behave as if its mass were negative. The same is valid for its bulk modulus – in antiresonance the material will expand when pressure is applied to it, and contract when pressure is removed.

Metafluid with negative acoustic properties was proposed by Pendry and Li [14]. A relatively simple concept of a layered acoustic cloak has been proposed by Cummer and Schurig in 2007 [15] and further elaborated by Torrent and Sánchez-Dehesa [16] for the case of circular basis. In their contributions gradient acoustic metafluids are used to ensure negative response of a cloak and thus bend acoustic waves around the object without causing disturbance and scattering. The works by Gao et al [17] and Ma et al [18] investigated elliptical scatterers.

The importance of acoustic cloaking for concealment of underwater objects is obvious. One could avoid torpedoes that are directed by on-board sonar, conceal mines or submarines, etc.

In this contribution we analyze the possibility to utilize multilayer acoustic cloak based on gradient acoustic metamaterials for the concealment of macroscopic underwater objects with cylindrical shape (the often met form of military hardware for underwater actions) with circular and elliptical basis. We apply finite element modeling to simulate acoustic cloaking. We analyze different spectral ranges, from infrasound to audible frequencies.

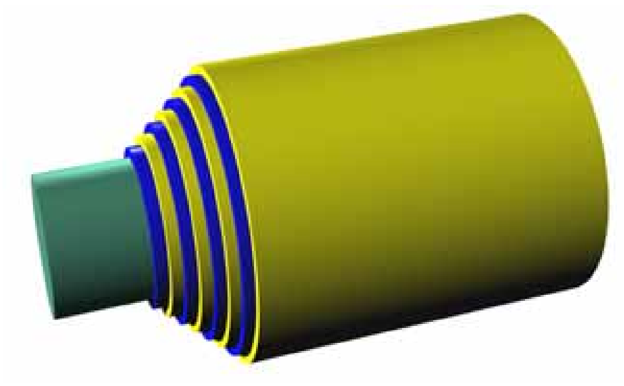
2. THEORY

Basic parameters of acoustic metamaterials are the bulk modulus β describing the resistance material gives to uniform compression and the mass density ρ, defined as the mass of material per unit of its volume. They determine the propagation of acoustic waves through such materials and define the speed of sound c through them.

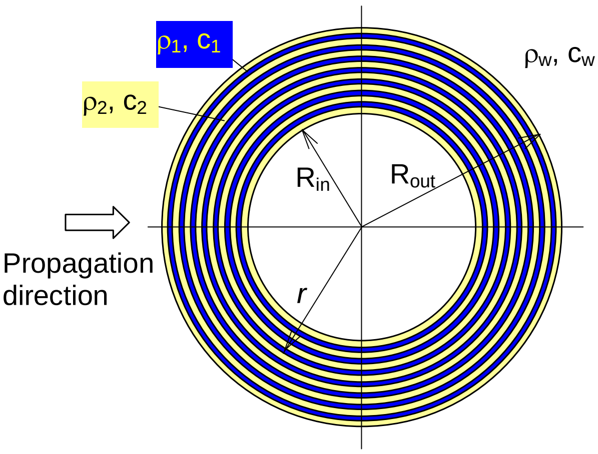
The partial differential equation describing spatial variation of total acoustic pressure p_{tot} is given as

$$-\nabla\left(\frac{\nabla p_{tot}}{\rho}\right)-\frac{\omega^2 p_{tot}}{\rho c^2}=0 \qquad (1)$$

where ω is the angular frequency of the sound wave.



Picture 2: Cloaking of cylindrical scatterer by alternating acoustic metamaterials.



Picture 3: Parameters of a cylindrical acoustic cloak: inner radius of cloak R_{in}, outer radius R_{out}, cloak is layered structure composed of graded metamaterial 1 (ρ_1, c_1) and metamaterial 2 (ρ_2, c_2). ρ_w and c_w are parameters of the surrounding medium (water).

First we assume that there is no scatterer (the object to be concealed). In that case we have only the background variation of pressure due to the presence of acoustic wave. The acoustic wave is longitudinal mechanical oscillation with sinusoidal change, i.e. it can be written as

$$p_b = p_0 \exp(-kr), \ k = \frac{\omega}{c} \tag{2}$$

where "b" stands for background, r is the position in space, p_0 is the background pressure if no acoustic wave is present and k is the standard definition for wave vector.

If a scatterer is present (the concealed object or this object plus cloak), the resulting pressure can be represented as a superposition

$$p_{tot} = p_b + p_{scat} \tag{3}$$

where "b" stands for "background" and "scat" means "scattered".

Contrary to the previous cases considered in literature, we performed our calculations for a realistic case of acoustic cloak submerged in sea water. To this purpose we utilized an empirical formula for the speed of sound in water [19]

$$\begin{aligned} v[m/s] = 1337.5 + 3.429t[°C] + 1.6722\,d[km] + \\ + 0.03048\,C_{NaCl} + 109.73 \end{aligned} \tag{4}$$

where t is temperature in degrees Celsius, d is depth in km, C_{NaCl} is salinity of water in percent.

Let us consider first the situation where the object to be concealed is a cylinder with a circular basis 2 m in diameter, Pic. 2. According to Cummar [15] and Torrent [16] a multilayered acoustic cloak in the form of a cylindrical shell is formed of two acoustic metamaterials alternating around the scatterer (inner cylindrical core).

The geometry and the dimensions of the system are shown in Pic. 3. The thickness of each single metamaterial layer is 2 cm, and the total thickness of the cloak is 1 m, i.e. $R_1 = 1$ m, $R_2 = 2$ m. The whole structure is submerged in sea water (subscript "w"). The properties of the both cloak materials are graded and the dependence of their acoustic parameters on the location within the cloak are given in a radial coordinate system in the following form [15, 16]: the relative mass density is

$$\rho_r = \frac{r}{r - R_{in}} \rho_w \tag{5}$$

$$\rho_\theta = \frac{r - R_1}{r} \rho_w \tag{6}$$

and the graded bulk modulus (Lamé coefficient) is

$$\lambda = \left(\frac{R_{out} - R_{in}}{R_{out}} \right)^2 \frac{r}{r - R_{in}} \lambda_w \tag{7}$$

Further we consider a more realistic situation where the basis of the cylinder is elliptical. In this work we utilize a mapping between points within the ellipse and the radial coordinate system. In this manner the gradient distribution presented by (5)-(7) is mapped to an ellipse with an arbitrary degree of flatness. This is achieved by representing inner and outer acoustic shield elliptical boundaries in polar coordinates, thus relative mass density of the shield is position dependable both radial and poolar coordinate. Two elliptical boundaries are described by their major and minor axis, a_{in} and b_{in} for inner boundary and a_{out} and b_{out} for outer boundary. Thus from (5), (6) and (7) parameters of our acoustic shield become:

$$\begin{aligned} R_{in}(\theta) &= \frac{a_{in} b_{in}}{\sqrt{(b_{in}\cos\theta)^2 + (a_{in}\sin\theta)^2}} \\ R_{out}(\theta) &= \frac{a_{out} b_{out}}{\sqrt{(b_{out}\cos\theta)^2 + (a_{out}\sin\theta)^2}} \end{aligned} \tag{8}$$

$$\rho(r,\theta) = \frac{r}{r - R_{in}(\theta)} \rho_w \tag{9}$$

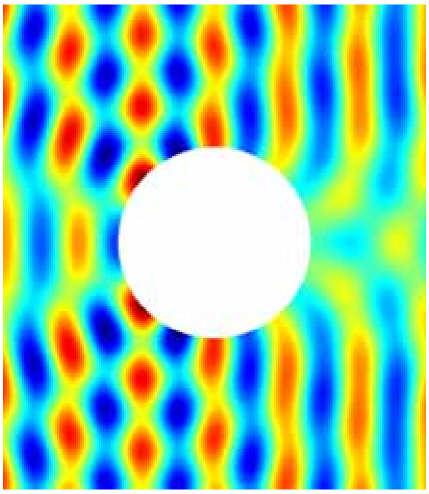
$$\lambda(r,\theta) = \left(\frac{R_{out}(\theta) - R_{in}(\theta)}{R_{out}(\theta)} \right)^2 \frac{r}{r - R_{in}(\theta)} \lambda_w \tag{10}$$

3. RESULTS

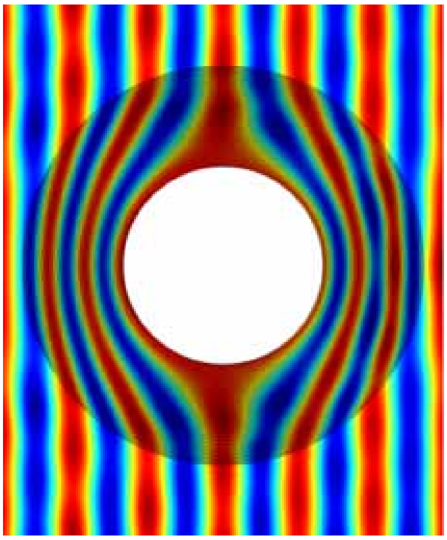
Picture 4 shows the distribution of acoustic waves when a simple plane wave is incident a cylindrical scatterer that disturbs its distribution. The calculation was done for a frequency of 2 kHz. No cloak is applied at this stage.

Pic. 5 shows the calculated total acoustic field (background + scattered component) if a 50-fold layered acoustic cloak is applied. The frequency is again 2 kHz. The presence of the multilayered cloak removes the disturbance and the field adopts the form as if no scatterer were present. A warping of the acoustic space is done according to eqs. (4)-(6) so that the field outside the cloak behaves the same as in the unperturbed case.

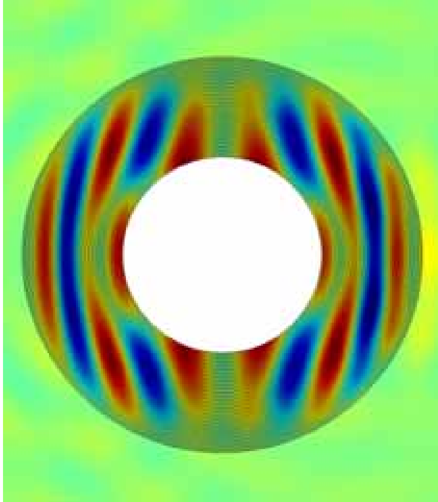
Picture 6 shows the distribution of only the scattered component of the incident sound wave at 2 kHz. It can be seen that the most of the scattering is compensated within the cloak structure itself. Thus outside of it only a weak disturbance is seen.



Picture 4: Total acoustic pressure map with cylindrical scatterer, 2 kHz. Highest pressure is 1.91 Pa (mapped dark red), lowest –1.69 Pa (dark blue)

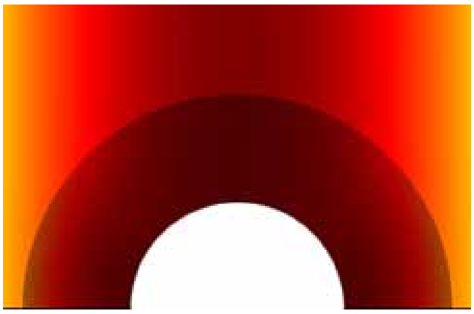


Picture 5: Total acoustic pressure map at a cylindrical scatterer surrounded by multilayered shell, 2 kHz. Highest pressure is 1.18 Pa (mapped dark red), lowest –1.18 Pa (dark blue)

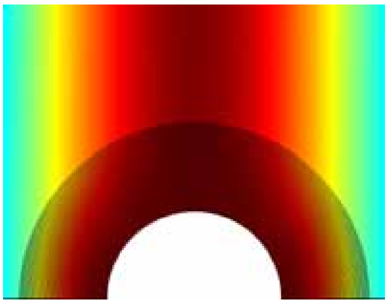


Picture 6: Scattered component of acoustic pressure map at a cylindrical scatterer surrounded by multilayered shell, 2 kHz. Highest scattered pressure is 1.45 Pa (mapped dark red), lowest –1.45 Pa (dark blue)

The next calculation is done for the case of infrasound. The operating frequency is 20 Hz, i.e. it is at the very brink of the audible range. Picture 7 shows the distribution of the total acoustic pressure in this case. The cylinder is deeply subwavelength and the role of the cloak is very small since the object itself is almost invisible to the interrogating signal. Only the upper half of the cylindrical structure is shown.



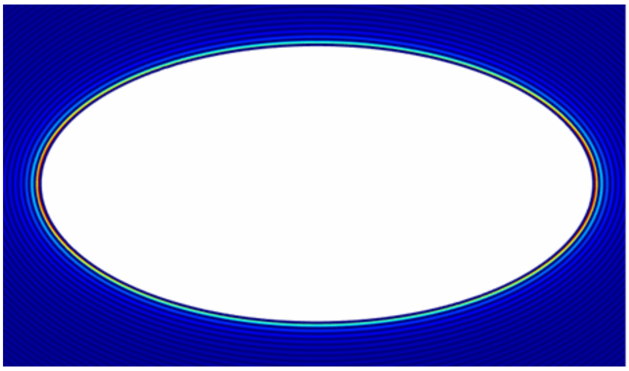
Picture 7: Total acoustic pressure map at a cylindrical scatterer surrounded by multilayered shell, 20 Hz. Highest pressure is 1 Pa (dark red), lowest 0.95 Pa (dark blue)



Picture 8: Total acoustic pressure map at a cylindrical scatterer surrounded by multilayered shell, 200 Hz. Highest pressure is 1 Pa (mapped dark red), lowest –0.2 Pa (dark blue)

Pic. 8 shows the map of the total acoustic pressure in the sound domain (200 Hz). The redistribution of the acoustic pressure within the cloak is readily seen.

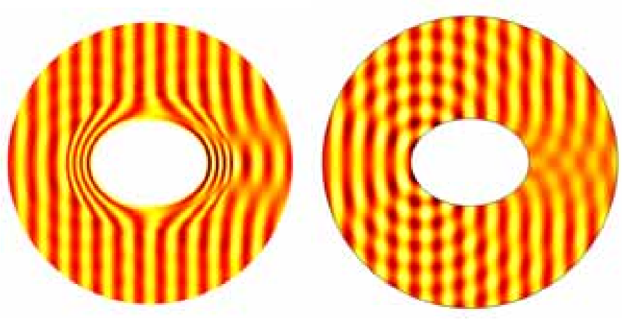
Further we investigate scatterers with elliptical basic. The calculated density distribution within a layered cloak with a thickness of 1 m is shown in Pic. 9. The gradient of density is readily seen.



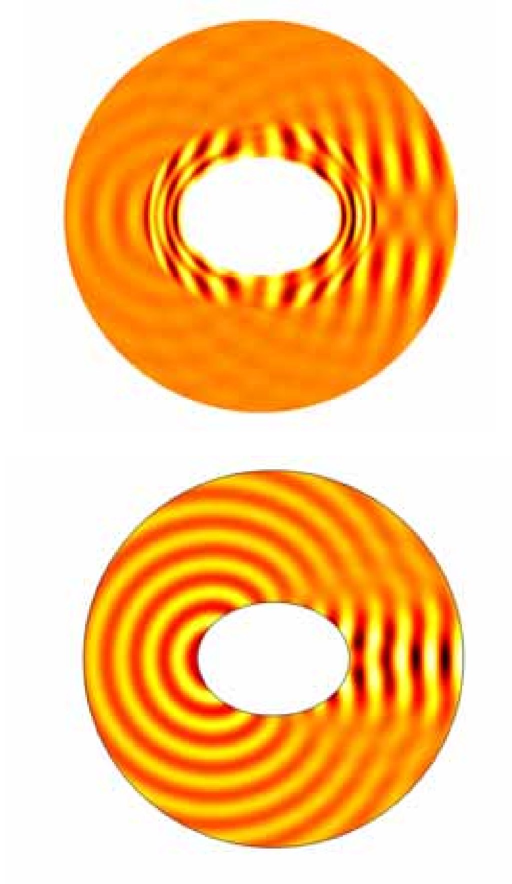
Picture 9: Spatial distribution of elliptical cloak density

The distribution of the acoustic pressure around a scatterer with elliptical basis is shown in the further figures. All the presented spatial distributions were calculated for a 2 KHz acoustic wave arriving from the left in the direction of the major axis. Obviously scattering will differ for acoustic waves arriving from different directions, contrary to the case of cylinders with a circular basis.

Picture 10 shows the total acoustic pressure distribution for the case when a scatterer with a major axis of 2 m and a minor axis of 1.5 m is considered. Pic. 10 left shows a situation when a layered acoustic cloak (50 layers, total thickness 1 m) is applied, while Pic. 10 right shows the situation without cloaking. A much larger disturbance in the latter case is readily observed. Picture 11 shows the same situation, but with scattered pressure shown instead of the total pressure. It can be seen that backscattering is strongly suppressed when using a cloak, especially useful for cloaking navy vessels where object detection is based on phase difference between emitted and backscattered wave. Forward scattering is also significantly decreased. A similar situation is observed for other directions of incident acoustic waves (not shown in this text).



Picture 10: Total acoustic pressure map (left) with multilayered elliptical acoustic cloak and (right) without acoustic cloak; scatterer is elliptical cylinder, minor axis 1.5 m, major axis 2 m, cloak thickness 1 m, frequency 2 kHz.

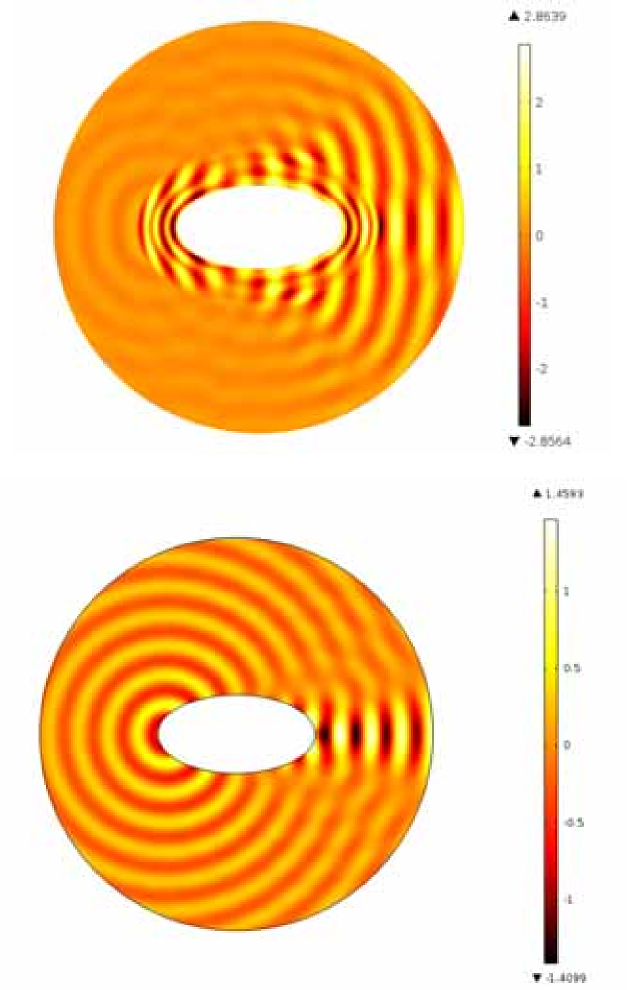


Picture 11: Scattered acoustic pressure map (top) with multilayered elliptical acoustic cloak and (bottom) without acoustic cloak; scatterer is elliptical cylinder, minor axis 1.5 m, major axis 2 m, cloak thickness 1 m, frequency 2 kHz.

We also considered the situation when the scatterer is a more flattened ellipse, with its axes 1 m and 2 m. The cloak is again with a constant thickness of 1 m, 50 layers. Compared to the situation presented in [ref], a better cloaking is observed.

4. CONCLUSION

We considered the possibility of fabricating a cloaking structure for acoustic concealment of cylindrical underwater objects. Layered acoustic cloaks with spatial variation (gradient) of mass density and bulk modulus are used for that purpose. We investigated the parameters of the cloaks for different operating frequencies of sonar, including infrasound and audible sound. We utilized finite element modeling to solve the partial differential equation governing the spatial distribution of acoustic pressure without a cloak and with it. We considered scatterers with circular and with elliptical basis. In both cases constant thickness layered cloaks were applied. It can be seen that in principle full tailoring of the path of acoustic waves around the camouflaged object (scatterer) is possible. This gives the opportunity to make sound waves avoid the object and render it invisible for sonar. Obviously a number of practical problems related with the fabrication of the metamaterial itself, as well as with adjusting its dimensions remains yet to be solved.



Picture 12: Scattered acoustic pressure map (top) with multilayered elliptical acoustic cloak and (bottom) without acoustic cloak; scatterer is elliptical cylinder, minor axis 1 m, major axis 2 m, cloak thickness 1 m, frequency 2 kHz.

ACKNOWLEDGMENT

This work has been funded by Serbian Ministry of Education, Science and Technological Development within the framework of the project TR 32008.

REFERENCES

[1] Chen, H., Chan, C. T., "Acoustic cloaking and transformation acoustics", *J. Phys. D,* 43(11) (2010).

[2] Norris, A. N., "Acoustic cloaking theory", *P. R. Soc. A,* 464(2097) (2008), 2411-2434.

[3] Cai, W., Shalaev, V., *Optical Metamaterials: Fundamentals and Applications,* Springer, Dordrecht, Germany, 2009; p 207.

[4] Ramakrishna, S. A., Grzegorczyk, T. M., *Physics and Applications of Negative Refractive Index Materials,* SPIE Press Bellingham, WA & CRC Press, Taylor & Francis Group, Boca Raton FL, 2009.

[5] Pendry, J. B., Schurig, D., Smith, D. R., "Controlling Electromagnetic Fields", *Science,* 312(5781) (2006), 1780-1782.

[6] Leonhardt, U., "Optical Conformal Mapping", *Science,* 312(5781) (2006), 1777-1780.

[7] Cai, W., Chettiar, U. K., Kildishev, A. V., Shalaev, V. M., "Optical cloaking with metamaterials", *Nat. Photonics,* 1(4) (2007), 224-227.

[8] Zhang, S., Xia, C., Fang, N., "Broadband acoustic cloak for ultrasound waves", *Phys. Rev. Lett.,* 106(2) (2011).

[9] Zigoneanu, L., Popa, B. I., Cummer, S. A., "Three-dimensional broadband omnidirectional acoustic ground cloak", *Nat. Mater.,* 13(4) (2014), 352-355.

[10] Deymier, P. A., *Acoustic metamaterials and phononic crystals*, Springer Verlag, Berlin Heidelberg, 2013.

[11] Lee, S. H., Park, C. M., Seo, Y. M., Wang, Z. G., Kim, C. K., "Acoustic metamaterial with negative modulus", *J. Phys.-Condens. Mat.,* 21(17) (2009).

[12] Li, J., Chan, C. T., "Double-negative acoustic metamaterial", *Phys. Rev. E,* 70(5 2) (2004), 055602-1-055602-4.

[13] Yang, Z., Mei, J., Yang, M., Chan, N. H., Sheng, P., "Membrane-type acoustic metamaterial with negative dynamic mass", *Phys. Rev. Lett.,* 101(20) (2008).

[14] Pendry, J. B., Li, J., "An acoustic metafluid: Realizing a broadband acoustic cloak", *New. J. Phys.,* 10(2008).

[15] Cummer, S. A., Schurig, D., "One path to acoustic cloaking", *New. J. Phys.,* 9(2007).

[16] Torrent, D., Sánchez-Dehesa, J., "Acoustic cloaking in two dimensions: A feasible approach", *New. J. Phys.,* 10(2008).

[17] Gao, D. B., Zeng, X. W., "Layered elliptical-cylindrical acoustic cloaking design based on isotropic materials", *Wuli Xuebao/Acta Physica Sinica,* 61(18) (2012).

[18] Ma, H., Qu, S., Xu, Z., Zhang, J., Chen, B., Wang, J., "Material parameter equation for elliptical cylindrical cloaks", *Phys. Rev. A*, 77(1) (2008).

[19] Wilson W. D. "Equation for the speed of sound in sea water", *J. Acoust. Soc. Amer*., 1960, vol.32, N 10, p.