

Broadband Acoustic Cloaking within an Arbitrary Hard Cavity

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This paper reports the design, fabrication, and experimental validation of a broadband acoustic cloak for the concealing of three-dimensional (3D) objects placed inside an open cavity with arbitrary surfaces. This 3D cavity cloak represents the acoustic analogue of a magician hat, giving the illusion that a cavity with an object is empty. Transformation acoustics is employed to design this cavity cloak, whose parameters represent an anisotropic acoustic metamaterial. A practical realization is made of 14 perforated layers fabricated by drilling subwavelength holes on 1-mm-thick Plexiglas plates. In both simulation and experimental results, concealing of the reference object by the device is shown for airborne sound with wavelengths between 10 cm and 17 cm.

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I. INTRODUCTION

Acoustic cloaking defines the phenomenon of acoustic concealing of objects embedded in a gas or a fluid. The concealing is obtained when the object is surrounded by a fluidlike shell (the cloak), which bends the impinging waves around the object in such a manner that they arrive in phase at the opposite side; i.e., the sound crosses the object without being distorted by scattering events. Acoustic cloaks for two-dimensional (2D) objects were described in 2007 by Cummer and Schurig [1], who translated into the acoustics realm the design procedure employed for electromagnetic (EM) waves [2,3]. For concealing 2D and even three-dimensional (3D) objects embedded in a gas or an inviscid fluid, the cloak's acoustic parameters are obtained using transformation acoustics. The resulting materials have an inhomogeneous and anisotropic mass density. However, the bulk modulus is scalar but its value is radially dependent [1,4]. In spite of the unavailability of these parameters in nature, research has been conducted showing the possibility of engineering acoustic metamaterials, which are artificial structures with extraordinary acoustic properties like tensorial mass density [5–8].

Though there are many theoretical studies and proposals of cloaking devices based on transformation acoustics [4,9–11] only a few experimental results have been reported so far [12]. More recently, the research on cloaking has been extended to flexural waves, where also *reduced* cloaks have been proposed [13] and experimentally reported [14]. The theoretical tool of coordinate transformation also has been extended to other areas of physics, such as heat flux, where thermal cloaking and thermal camouflage have been proposed [15,16] and experimentally realized [16,17].

The reason behind the difficulty of making feasible acoustic cloaks with perfect behavior is associated with the impossibility of engineering passive structures where the sound must travel with a phase velocity larger than that of the fluid background. It has been argued that such enhancement of the sound speed could be obtained by adding some physical mechanism, like temperature [18], but the designed cloak is not feasible. Another alternative consists of designing cloaks based on scattering cancellation [19–22], but the resulting cloaks have narrow-band operation and the practical realizations reported so far are only axisymmetric [20,22].

Transformation acoustics also has been applied to designing ground cloaks for the concealing of 2D and 3D objects on top of flat surfaces [23,24]. The parameters of the resulting cloaking shells consist of positive-index anisotropic fluidlike material, which are achieved using artificial structures consisting of multiple layers of

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perforated plates. More recently, Kan *et al.* [25] reported the demonstration of a 2D ground cloak operating in curved surfaces with cylindrical symmetry. In brief, they apply coordinate transformation to solve the problem of hiding cylindrical objects located in front of a corner made of two flat semi-infinite planes. A reduced version of the designed cloak is designed and a cloak prototype is characterized. However, the problem of rendering acoustically invisible an arbitrary 3D object placed inside an open cavity with arbitrary curved surfaces (i.e., a true 3D cavity) still remains as a challenge. The resulting acoustic illusion can be considered as the analog in acoustics of the optical illusion produced by a *magician hat*.

This work reports the design and practical realization of a magician hat for acoustic waves. This device represents a 3D acoustic cloak, allowing the concealing of 3D arbitrary objects located inside an open cavity with arbitrary boundaries. The proposed 3D device creates the illusion of an empty cavity though, in fact, it is partially occupied. The resulting 3D cloak consists of an acoustic metamaterial which is obtained using an array of perforated plates with subwavelength holes. Due to the absence of resonant elements, the device operates over a wide bandwidth and it is effective for a broad range of incident angles. The fabricated device could be considered as a generalization of the reported 2D cloaks [23–25] but here we are dealing with true 3D objects surrounded with arbitrary surfaces with no ideal assumptions (like 2D spaces or infinite, flat, reflecting planes).

This article is organized as follows. After this introduction, Sec. II reviews the transformation technique applied to designing the acoustic-cavity cloak and its performance at distances near and far from the cavity aperture. Then, Sec. III presents details of the fabricated sample together with its experimental characterization. The results are discussed in Sec. IV, which analyzes results in terms of the so-called visibility factor. Finally, Sec. V summarizes the main findings of this work.

II. THEORY

We have considered an open cavity consisting of a truncated cone with height 15 cm and ellipsoidal section. This cavity has noncylindrical symmetry and could be considered as a simple example of a cavity with arbitrary shape. The semiaxes of the ellipsoid corresponding to the cavity aperture are 12 cm and 18 cm. Figure 1(a) shows a photograph of the constructed cavity.

The cloak is designed following the coordinate-transformation technique. The relationships between the tensorial effective mass density ($\bar{\rho}$) and the scalar bulk modulus (B) in the virtual (v) and real (r) systems is given by $\rho^{r-1} = \mathbf{H}\bar{\rho}^{-1}\mathbf{H}^T/\det(\mathbf{H})$ and $B^r = \det(\mathbf{H})B^v$, where \mathbf{H} is the Jacobian defined as $\mathbf{H} = \text{diag}\{\partial x'_1/\partial x_1, \partial y'_1/\partial y_1, \partial z'_1/\partial z_1\}$.

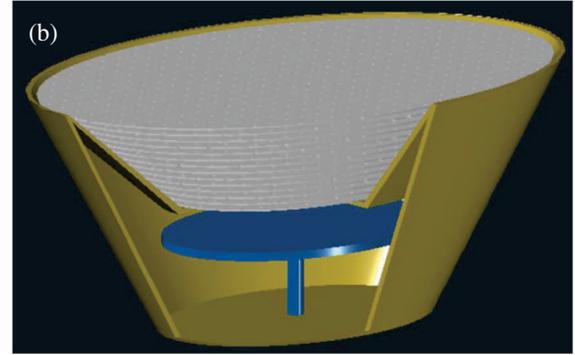
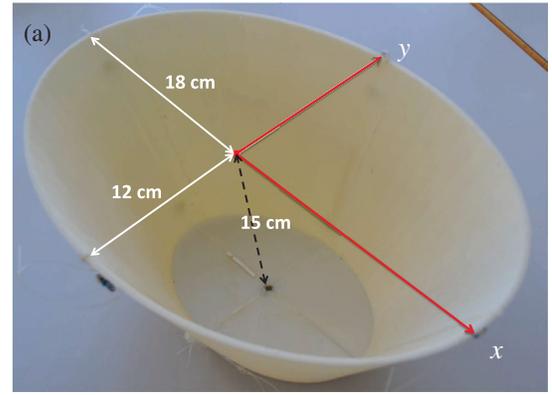


FIG. 1. (a) Photograph of the acoustic cavity manufactured using a 3D printer. It consists of a truncated cone with height 15 cm and the semiaxes of the ellipsoidal aperture has 18 cm and 12 cm. (b) Scheme of the cavity containing a 3D object (in blue) and with the metamaterial cloak on top (gray layers). (c) Photograph of cavity with the reduced cloak inserted in the cavity.

Since the physical space can be regarded as a compressed conformal transformation of the virtual space, the mapping between the physical and virtual spaces is specified by $x'_1 = x_1$, $y^r = y_1$, and $z^r = z_1/n_c$, where n_c is the index of compression, which can take an arbitrary value. In this work, we consider the value 2.13. $\rho_v(x, y, z)$ and $B_v(x, y, z)$ are the position-dependent parameters in the chosen virtual space. Therefore, the cloak parameters

are $\rho^r(x, y, z) = \text{diag}\{1/n_c, 1/n_c, n_c\}$ and $B^r(x, y, z) = B^v(x, y, z)/n_c$. Because of the symmetry of the unit cell, there are only two independent density components, ρ_{\parallel} and ρ_{\perp} , representing the parallel and perpendicular components, respectively, to the x - y plane [see Fig. 1(a)].

Following the transformation procedure, the material parameters required for the perfect cloak are $\rho_{\parallel} = 0.47\rho_0$, $\rho_{\perp} = 2.13\rho_0$, and $B = 0.47B_0$, where ρ_0 and B_0 are the mass density and bulk modulus of the surrounded background (air in this work). These parameters indicate that the cloak should be made of an anisotropic fluid with a parallel component of the density smaller than the air density. In addition, its bulk modulus must be smaller than that of air. This type of fluidlike material, less dense and less rigid than air, is extremely difficult to engineer by passive structures. To overcome this issue, we design a *reduced* cloak whose parameters are augmented in the same ratio, thus becoming $\rho_{\parallel} = 1.2\rho_0$, $\rho_{\perp} = 5.4\rho_0$, and $B = 1.2B_0$. These parameters imply that the acoustic impedance of the reduced cloak is not matched with that of air, although the phase information is conserved. Therefore, unavoidable reflections appear between the cloak and the air that would not occur for the perfect cloak [18]. However, the refractive index of the proposed metamaterial is not altered with respect to the original, so the resulting device is able to create a good illusion of concealing a given reference object.

A. Designing the artificial structure representing the reduced cloak

To achieve the required parameters of the proposed reduced cloak, we employ a layered structure consisting of 14 perforated Plexiglas plates. Figure 1(b) shows a schematic representation of the cavity (yellow) together with the inserted object (blue) and the metamaterial cloak (gray).

Each plate consists of a square lattice of subwavelength circular holes with lattice period $a = 5$ mm, which is small enough to ensure the validation of the effective medium approximation in the range of wavelengths employed experimentally, i.e., in the domain $10 \text{ cm} \leq \lambda \leq 17 \text{ cm}$. The anisotropic unit cell is shown in Fig. 2(a), where the plate thickness $t = 1$ mm, and the hole diameter $D = 1.6$ mm. The distance between perforated plates $d = 5$ mm. A photograph of the constructed cavity with the cloak is shown in Fig. 1(c)

The effective parameters of the multilayer structure are calculated with the retrieval method proposed in Ref. [1]. The wavelength dependence of the resulting effective parameters are represented in Figs. 2(b) and 2(c), corresponding to the case where the wave impinges the plate normally and to the case where the incident wave travels along the plate, respectively. The red line is the normalized effective mass density and the blue line is the normalized bulk modulus. For the bulk modulus, it can be observed that $B_{\perp} \approx B_{\parallel}$ and, therefore, the bulk modulus can be

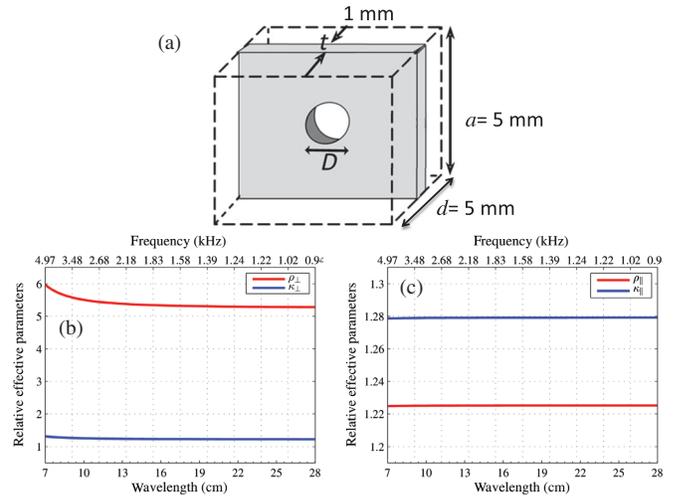


FIG. 2. Unit cell of the anisotropic structure and its effective acoustic parameters. (a) Illustration of the unit cell. (b),(c) Retrieved effective parameters of the structure as a function of frequency when the wave normally impinges on the plate (b), and when the wave travels parallel to the plate (c). The red line is the effective mass density and the blue line is the bulk modulus, both parameters being normalized to the properties of air.

considered as a scalar magnitude. Note that the parallel component of the effective mass density ρ_{\parallel} is much larger than the perpendicular one ρ_{\perp} . This structure increases the momentum in the direction perpendicular to the plates, while having little effect in the direction parallel to the plates. It is also observed that, in the range of wavelengths experimentally studied (above $\lambda = 10$ cm), the effective parameters nearly remain constant and, consequently, the fabricated device is able to work in this broadband region. For wavelengths below 10 cm, the effective parameters are dispersive and the metamaterial approach is not valid.

B. Cloak performance near the cavity aperture

The scattering properties of the cloaks previously described (ideal and reduced), together with those of the empty cavity and the cavity with the object, are shown in Fig. 3, which reports the total pressure pattern on the x - z plane obtained from the 3D finite-element (FE) method. Numerical simulations using COMSOL Multiphysics are performed by illuminating the cavity with an incident sound with a plane wavefront perpendicular to the z axis. The external boundaries of the simulation domain are nonreflective, while the boundaries of the cavity shell and the object are considered rigid. Figure 3 shows snapshots at the chosen wavelength of $\lambda = 13$ cm, corresponding to the frequency $f = 2680$ Hz (obtained by considering a speed of sound in air of $c_0 = 348$ m/s).

Figure 3(a) depicts the field resulting from the scattering between the impinging sound and the empty cavity at the

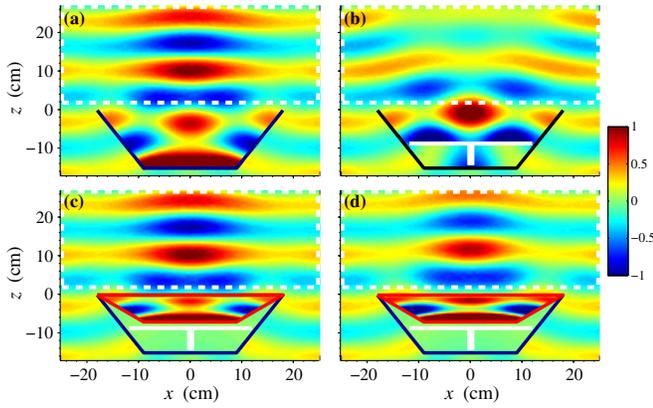


FIG. 3. Calculated total pressure field (real part) obtained from finite-element simulations for the different configurations of the cavity: (a) empty, (b) with the object inside, (c) with the object and the ideal cloak on top, and (d) with the object and the reduced cloak. The object is represented using thick white lines while the cloak's boundaries are represented with red lines. The dashed lines enclose the area to be experimentally scanned. The impinging sound with frequency 2.68 kHz has a perfect plane wavefront along the z axis. For animations of the instantaneous fields, see Video 1.

given frequency. A standing wave is observed along the z axis due to reflections by the cavity boundaries, which behave as rigid surfaces. Figure 3(b) reports how the initial pattern is distorted when the reference object, having a mushroomlike profile, is inserted in the cavity. After covering the object with the ideal cloak, Fig. 3(c) shows that the standing-wave pattern outside the cavity is perfectly recovered and, therefore, the acoustic illusion is created. Finally, in Fig. 3(d), it is observed that the standing-wave profile corresponding to the reduced cloak is slightly different from that of the ideal cloak, but it is good enough for the purpose of its practical realization. Motion pictures showing the time evolution of the calculated pressure maps of the cavity, the cavity with the object and the reduced cloak for two selected frequencies, 2.68 kHz and 3.48 kHz, are presented in Videos 1 and 2, respectively. Additional frequencies are also explored, confirming the wide-band operation of the designed cloak devices.

We should also remark that the designed cloak operates for a broad range of impinging angles, as can be observed in Video 3, which shows the time evolution of the pressure maps obtained for an impinging wave tilted 20° with respect to normal.

C. Cloak performance at distances far from the aperture

The performance of the cloak at the far field is also numerically studied and the polar plots of the radiation profiles on the x - z and y - z planes are shown in Figs. 4 and 5 for the wavelengths of 13 cm and 10 cm, respectively.

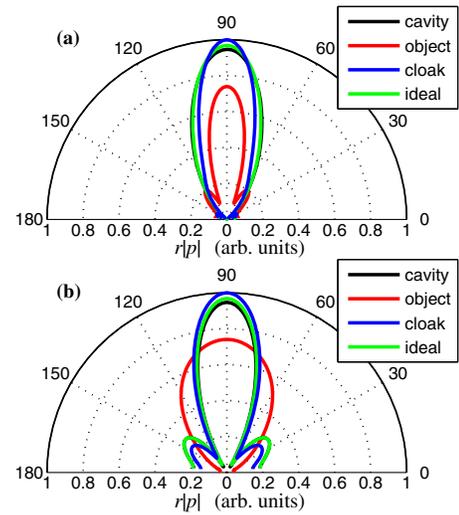


FIG. 4. Polar plots of the radiation profile calculated at the far field for the (a) x - z plane and (b) y - z plane. The colored lines define the profiles obtained for the empty cavity (black), the cavity with a mushroomlike object (red), the cavity with the object and the perfect cloak (green), and the expected profile when the reduced cloak is considered (blue). Results are obtained with a wavelength of 13 cm (2.68 kHz).

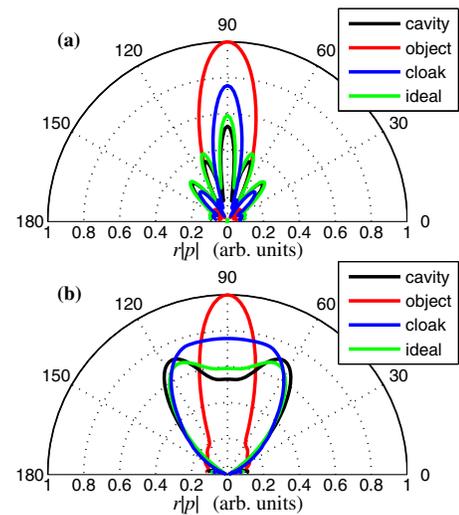


FIG. 5. Polar plots of the radiation profile calculated at the far field for the (a) x - z plane and (b) y - z plane. The colored lines define the profiles obtained for the empty cavity (black), the cavity with a mushroomlike object (red), the cavity with the object and the perfect cloak (green), and the expected profile when the reduced cloak is considered (blue). Results are obtained with a wavelength of 10 cm (3.43 kHz).

The radiation profiles are calculated from the expression $r|p(r, \theta)|$, for $r \rightarrow \infty$. A strong distortion is observed when the profiles obtained for the empty cavity (black lines) are compared with those of the cavity with the object

(red lines). However, it is remarkable that the profiles for the ideal cloak (green lines) and the reduced cloak (blue lines) are practically the same and both are similar to the profile of the empty cavity.

From the results shown in Figs. 4 and 5, we conclude that the performance of the reduced cloak is comparable with that of the ideal cloak at distances far from the cavity. Therefore, the reduced cloak is considered good enough for producing the illusion associated with a true acoustic magician hat. However, let us point out that results in Fig. 5, corresponding to a relatively high frequency (3.43 kHz), indicate that the reduced cloak does not work as well as in the case shown in Fig. 4, corresponding to a lower frequency (2.68 kHz). The two reasons explaining this behavior. First, the effect of the impedance mismatch becomes more important for acoustic waves with shorter wavelengths. And second, the wave becomes sensitive to the parameter deviation from the ideal values for shorter wavelengths.

Profiles in Figs. 4 and 5 are calculated for the viewpoints defined by both symmetry planes x - z and y - z . Figure 6 shows the results for viewpoints defined by planes rotated by an angle of 0.3π with respect to the symmetry planes. Better contrast can be observed because the profile for the reference object (red line) is much different from the other cases (blue and black lines), which indicates that the object would be easily detected at such viewpoints without the cloak. The far-field profile of the reduced cloak (blue line) practically overlaps those of the empty cavity and the empty cavity, indicating that the cloak works well under these circumstances.

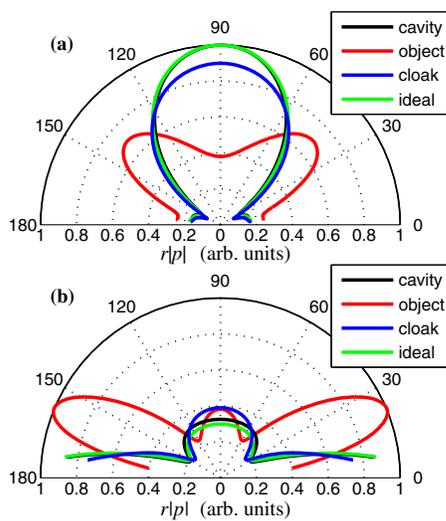


FIG. 6. Far-field radiation patterns for a viewpoint tilted 0.3π with respect to the (a) x - z and (b) y - z planes for a wave impinging on the empty cavity (black lines), the cavity with object (red lines), the ideal cloak (green lines), and the reduced cloak (blue lines). Results are obtained with a wavelength of 13 cm (2.68 kHz).

III. EXPERIMENT

The previous theoretical findings are experimentally verified by fabricating the cavity and the metamaterial cloak with the properties of the reduced cloak. A comprehensive acoustic characterization of the structures is conducted inside an anechoic room as explained below.

First, the cavity shell is fabricated with a 3D printer which uses ABS thermoplastic as the building material. In addition, the reduced cloak is constructed using 14 perforated Plexiglas plates whose parameters are obtained from a rigorous design procedure explained in Sec. II A. A photograph of the fabricated cavity with the cloak on top is shown in Fig. 1(c). The materials employed in the construction of the cavity and the cloak are acoustically rigid in the range of frequencies explored.

The different samples (empty cavity, cavity with the object, and cavity with the object plus the cloak) are separately characterized in an anechoic chamber with dimensions $8 \times 6 \times 3$ m³. During the measurement process, a B&K 4958 microphone attached to two combined linear steppers is moved in order to perform a 2D sweep on the 50×25 cm² area defined in Fig. 3 with white dashed lines. The robots scan this area in the x - z and y - z planes with a spatial resolution of 1 cm. Moreover, an additional robot allows turning the sample in such a manner that its response could be measured as a function of the incident angle. The impinging wave is provided by a column loudspeaker placed at 4 m from the sample and aligned with it (see Fig. 7). A chirp consisting of a frequency sweep between 2 and 4 kHz is used as the excitation signal. Taking into account the wavelength of the emitted signals, we can consider that the wavefronts are plane when the sound arrives at the sample. The amplitude and phase of the total field are obtained by processing the recorded signal through

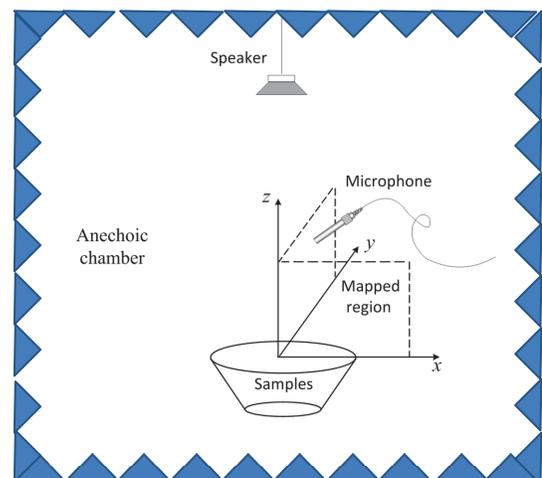


FIG. 7. Scheme of the experimental setup employed in mapping the pressure field inside the anechoic room. The z - x and z - y planes are depicted, together with the speaker and microphone.

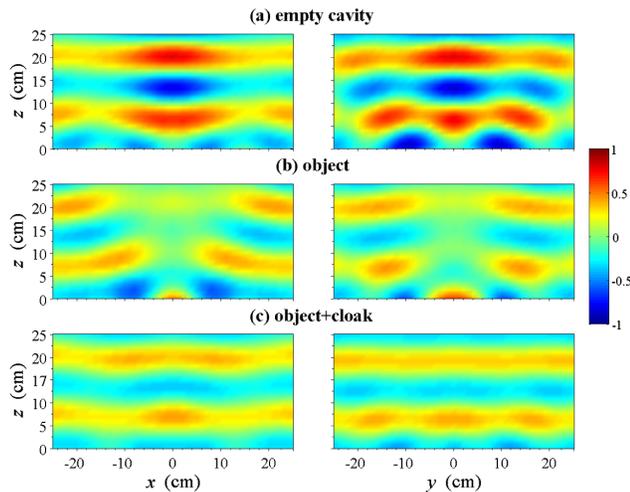


FIG. 8. Snapshots of the pressure maps measured at 2.68 kHz. Maps on the left (right) column represent the real part of the total pressure measured on the x - z (y - z) plane for the three cases of interest: (a) empty cavity, (b) cavity with the object, and (c) cavity with the object and the cloak. For animations of the instantaneous fields, see Video 4.

a Fourier transform. The presence of random noise is reduced by averaging the responses of several emissions.

IV. RESULTS AND DISCUSSION

Figure 8 shows the real part of the total pressure measured in the scanned area. The 2D maps taken in both the x - z (left panels) and y - z (right panels) planes are in good agreement with FE simulations. As predicted by the simulations, the comparison between experimental data in Fig. 8(a) and Fig. 8(b) shows that a strong distortion of the field is obtained when an object is put inside the cavity. Finally, in Fig. 8(c), it is observed that the field pattern of the empty cavity is practically recovered when the cloak is added to the cavity. Motion pictures showing the time evolution of the measured pressure maps for two selected frequencies, 2.68 kHz and 3.48 kHz, are presented in Videos 4 and 5, respectively.

The comparison between pressure levels in Figs. 8(a) and 8(c) shows that some attenuation appears in the structure with the cloak. This effect is due to unavoidable losses in the metamaterial cloak. A similar effect was also observed in all the reported cloaks consisting of layers of perforated plates [14,23–25]. In terms of pressure amplitude, we estimate that the fabricated cloak produces a reduction of about 25% of the pressure amplitude measured without the cloak. Regarding this issue, we have to remember that absorption due to viscous-thermal effects by microperforated plates is a strong and well-known phenomenon [26]. For the case of perforated plates made of millimeter-sized holes and moderated filling fraction, as in our cloak, the absorption is much smaller but non-negligible, as has been recently proven in a different context [27].

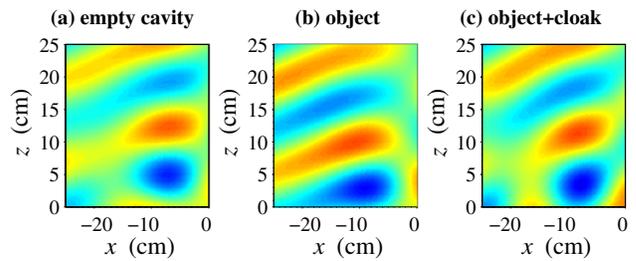


FIG. 9. Snapshots of the pressure maps measured at 2.68 kHz ($\lambda = 13$ cm) with an incident angle of 20° . Maps represent the real part of total pressure measured on the x - z plane for (a) empty cavity, (b) cavity with the object, and (c) cavity with the object and the cloak. For animations of the instantaneous fields, see Video 6.

The dependence on the impinging direction is also verified for three different directions, 10° , 20° , and 30° . It is observed that the object disturbs the 2D field pattern more weakly for increasing values of incident angles. As an example, Fig. 9 shows snapshots of the cloak performance for an incident wave tilted 20° with respect to normal. Video 6 shows the time evolution of the measured pressure maps. These experimental data confirm that the fabricated cloak works as a device capable of acoustically concealing an object located inside a cavity with arbitrary hard boundaries and for a broad range of incident directions.

In order to quantify the cloak performance in a single number, we have defined a frequency dependent *visibility* factor γ , inspired in the one employed to characterize cloaks in free space [12,20,22]. For example, for the data taken on the x - z plane,

$$\gamma_{xz}(\omega) = \frac{1}{T} \int \frac{\int |\text{Re}[p_2(x, z) - p_1(x, z)]| dx dz}{\int (|p_2(x, z)| + |p_1(x, z)|) dx dz} e^{i\omega t} dt, \quad (1)$$

the time averaging is performed over the period T corresponding to the given angular frequency ω . The spatial integrals contain the pressures p_1 and p_2 to be compared in the selected area, and the integrals are calculated inside that area. So, γ provides a quantitative estimation of the disparity of two field maps. Note that p_1 is here chosen as the field corresponding to the empty cavity sample, which is considered the reference field. In the previously studied cloaks [12,20,22], the reference field corresponds to the sound wave propagating in free space. On the other hand, p_2 is the field obtained for a different sample. For the cloak sample, a value $\gamma = 0$ means perfect concealing of the object. Results obtained for both x - z and y - z planes are depicted in Fig. 10, where the wavelength dependence of the visibility factors obtained from the measurements (symbols) are compared with those obtained from FE simulations (continuous lines). It is noted that the

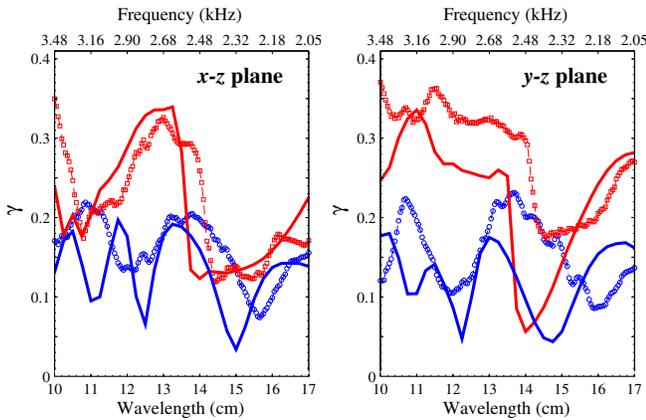


FIG. 10. Visibility factor γ as a function of the wavelength calculated from the measurements (symbols) and from the finite-element simulations (continuous lines). The red data correspond to the sample with the object inside the cavity while the blue data correspond to the cavity with the cloak and the object.

parameters experimentally obtained basically reproduce the behavior of the ones numerically calculated. Though the fabricated cloak does not provide the acoustic parameters of the perfect cloak, the resulting device (blue data) significantly reduces the visibility factor with respect to that of the object (red data). It is also observed that γ for the cloak device presents oscillations as a function of the wavelength. This effect is due to the impedance mismatch between cloak and air produced by the reduced set of acoustic parameters [18]. The averaged values of γ in the analyzed frequency domain are 0.12 and 0.15, corresponding to simulations and measurements, respectively. These values, which are only slightly above the zero level (defining perfect concealing) support our claim of the wide-band operation of our reported cloak.

V. SUMMARY

In summary, we have shown that 3D objects located inside a cavity with arbitrary curved surfaces can be efficiently concealed from an external sound using a cloak designed with transformation acoustics. The designed cloak consists of an acoustic metamaterial with an anisotropic mass density, which is engineered with a stack of perforated layers with subwavelength holes. Though the fabricated cloak has a reduced set of acoustic parameters, its performance shows an broadband operation for a large range of incident directions. The functionality here described represents the acoustic analogue of a magician hat, creating the illusion that a cavity filled with a 3D object is completely empty.

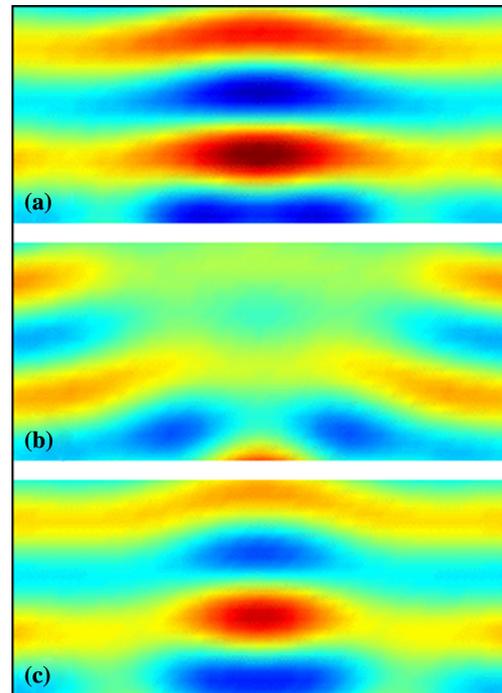
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W. W. K. and V. M. G.-C. contributed equally to this work.

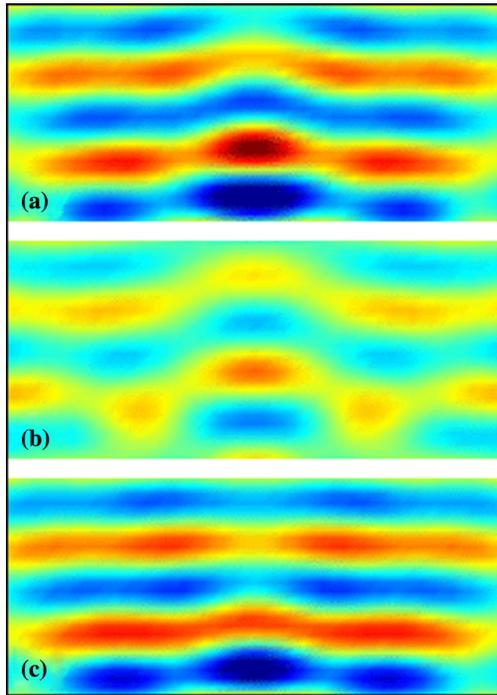
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APPENDIX:

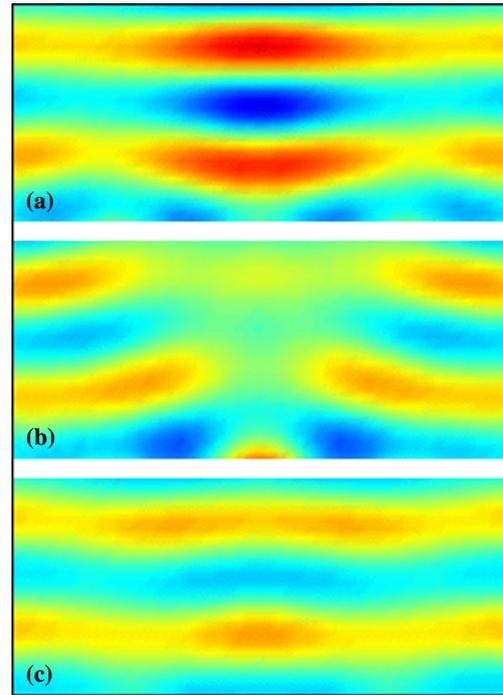
The dynamics of the total pressure field are demonstrated by Videos 1–6 from sequences of snapshots taken along one period. Each image is obtained by calculating or measuring the image at specific time intervals within a period.



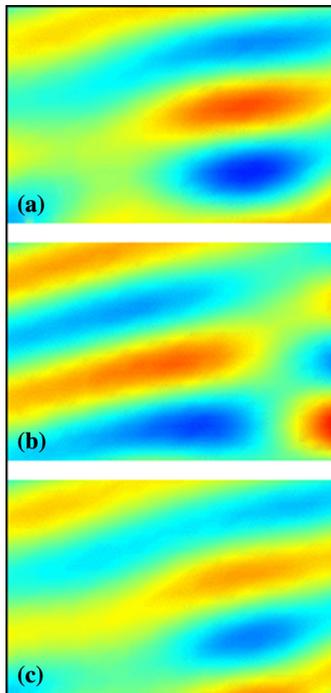
VIDEO 1. Motion picture showing the calculated pressure map on the x - y plane for (a) the empty cavity, (b) the cavity with a mushroomlike object, and (c) the cavity with the object and the cloak. The sound impinges the cavity at normal incidence and has a frequency of 2.68 kHz ($\lambda = 13$ cm).



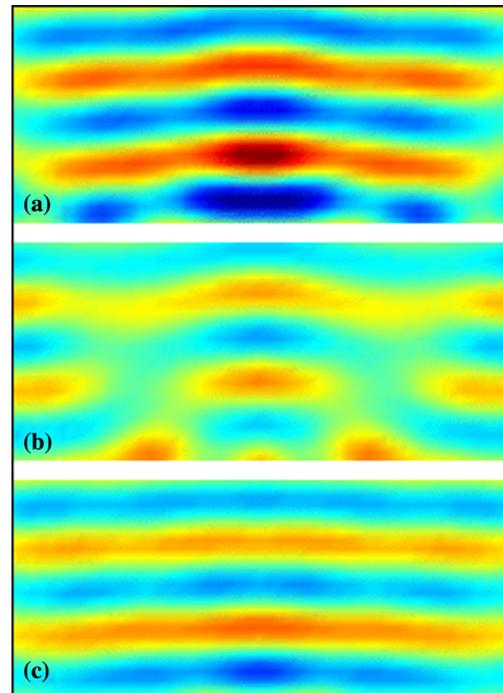
VIDEO 2. Motion picture showing the calculated pressure-field pattern in the x - y plane for (a) the empty cavity, (b) the cavity with a mushroomlike object, and (c) the cavity with the object and the cloak. The sound impinges the cavity at normal incidence and has a frequency of 3.48 kHz ($\lambda = 10$ cm).



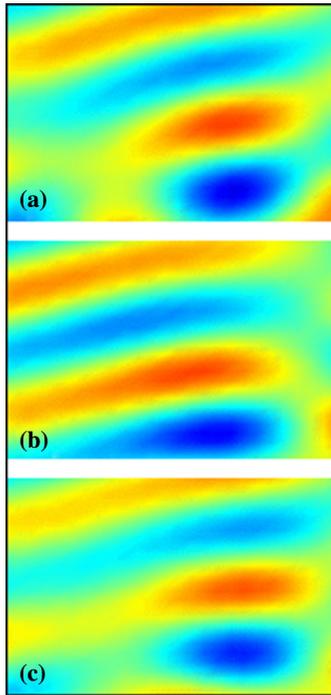
VIDEO 4. Motion picture showing the experimentally measured pressure map on the x - y plane for (a) the empty cavity, (b) the cavity with a mushroomlike object, and (c) the cavity with the object and the cloak. The sound impinges the cavity at normal incidence and has a frequency of 2.68 kHz ($\lambda = 13$ cm).



VIDEO 3. Motion picture showing the calculated pressure map on the x - y plane for (a) the empty cavity, (b) the cavity with the object, and (c) the cavity with the object and the cloak. The sound has a frequency of 2.68 kHz ($\lambda = 13$ cm) and the impinging angle is 20° , tilted with respect to the normal.



VIDEO 5. Motion picture showing the experimentally measured pressure map on the x - y plane for (a) the empty cavity, (b) the cavity with a mushroomlike object, and (c) the cavity with the object and the cloak. The sound impinges the cavity at normal incidence and has a frequency of 3.48 kHz ($\lambda = 10$ cm).



VIDEO 6. Motion picture showing the experimentally measured pressure map on the x - y plane for (a) the empty cavity, (b) the cavity with the object, and (c) the cavity with the object and the cloak. The sound has a frequency of 2.68 kHz ($\lambda = 13$ cm) and the impinging angle is 20° , tilted with respect to the normal.

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