The Sound of Perfection Thanks to the Modeling of Acoustic Metasurfaces

Acoustic metasurfaces are carefully engineered to control, direct, and manipulate sound waves in order to produce a specific acoustic property (e.g., a negative refractive index) that is not readily available in nature. A research team from the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland has simulated a novel "active" acoustic metasurface that could be used for enhancing the acoustics of concert halls and soundproof homes or damping irritating engine sounds during a flight.

by **GEMMA CHURCH**

FIGURE 1. Active Electroacoustic Resonator prototype. Image credit: EPFL/Alain Herzog.

A fundamental constraint of conventional acoustic treatments is that their dimensions limit their use frequency-wise (the thinner, the lesser the performance toward low frequencies), or that they rely on resonances to enhance their acoustic effect and are therefore restricted to a very narrow frequency band. For example, a membrane absorber (bass trap) placed in the corner of a recording studio to absorb low-frequency sounds that build up and interfere with the quality of the audio being produced only affects a limited frequency range around its resonance. However, these nuisance low frequencies usually span the 20 to 200 Hz range and a single acoustic treatment cannot absorb over this range of frequencies.

⇨ DIRECTING WAVEFRONT TRAFFIC

It is not practical to implement a design providing sound absorption at low frequencies, as the resulting structure would be too bulky and too difficult to optimize. Hervé Lissek, head of the acoustics group at the EPFL (École Polytechnique Fédérale de Lausanne), said: "Traditional membrane resonator capabilities are restricted to a range of just a few hertz, a limitation that precludes their mainstream application. Our idea was to develop a design that was broadband and active in nature." This led to the development of the Active Electroacoustic Resonator (AER) concept, where a conventional loudspeaker is used as a membrane absorber; the acoustic behavior of which can be modified by electric means (Figure 1).

With the knowledge gained from examining AERs, Lissek and his team tackled the concept of acoustic metasurfaces. An acoustic metasurface is basically a surface composed of small acoustic elements (membranes, small perforations, cavities, etc.), which are engineered to provide, as a whole, novel acoustic properties that each individual element does not provide by itself. In the metasurface concept, the assembly confers the acoustic properties down to wavelengths that are much longer than the size of each element (these unit cells are thus qualified as "subwavelength"). The metasurface can then either be engineered to provide sound absorption or direct wavefronts reflected over the metasurface toward a prescribed angle.

⇨ ACTIVE ADAPTION COULD BRING A RAINBOW OF SOUND

In order to model an acoustic metasurface, you must break that surface down into subwavelength unit cells to artificially reshape the acoustic wavefront and produce the desired result. The active acoustic metasurface proposed by Lissek and his team consists of a surface array of subwavelength loudspeaker diaphragms, each with programmable individual active acoustic impedances allowing for local control over the different reflection phases over the metasurface.

An active control framework is used to control the reflection phase over the metasurface. This is derived from the AER concept, where AERs can be tuned or modified through electroacoustic control schemes (Figure 3). Lissek explained: "We can change the way this metasurface reacts to a sound profile by electrically tweaking the membranes. Furthermore, this allows the membranes to actively adapt to the incoming sound. For example, if you are trying to mask the engine noise of an aircraft, the active nature of the active acoustic metasurface means it will change as the frequency of the engine changes during the different phases of flight, which could be in the range of some hundreds up to a few thousands of hertz." In an AER, the controller is known to achieve a wide variety of acoustic impedances on a single loudspeaker diaphragm used as an acoustic resonator, with the possibility to shift its resonance frequency by more than one octave.

You could even take this concept to reflect sound waves in a prescribed manner. Lissek added: "If broadband

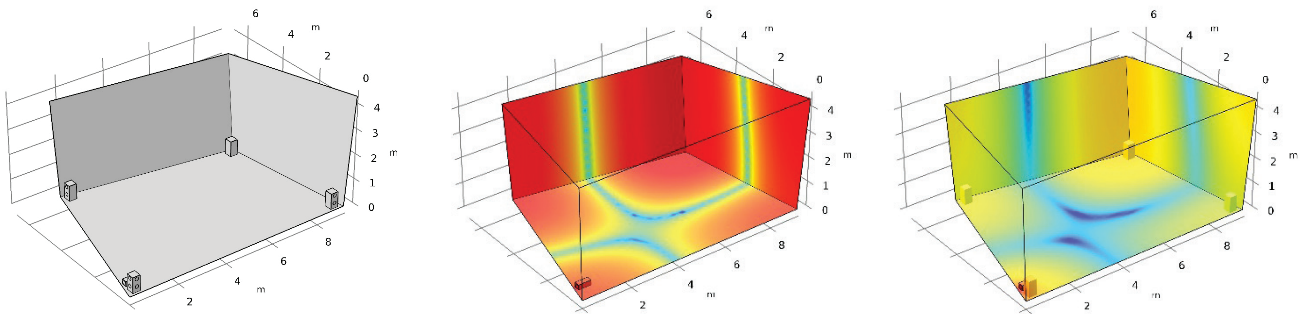

FIGURE 2. Left: Geometry of the reverberant chamber with four AER prototypes at the 4 corners. Middle and right: Sound pressure level distribution in the chamber excited on mode 110 at 35.3 Hz without and with absorbers, respectively.

noise (the acoustic counterpart of white light) is incident on an acoustic metasurface, then the acoustic metasurface could split noise, acting as an acoustic prism where you direct each constitutive frequency toward different directions. From an artistic perspective, there are many fascinating implications, as you would unleash a rainbow of sound, but the most forthcoming applications are primarily in noise reduction."

⇨ NUMERICAL SIMULATION INFORMS ACOUSTIC DESIGN

There are many complex phenomena that must be taken into account when simulating an acoustic metasurface and the surrounding acoustic environment. Lissek says "COMSOL Multiphysics gives us the ability to assess the sound performance of the devices that we design. What's more, it gives us a precise insight into the physics of the

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Let's go back to our previous example of a recording studio and extend it so we now have four small active absorbers (Figure 2) sitting in the corner of a room to absorb low-frequency sounds. To simulate how these devices will absorb and affect the sound within the room, you need to know the sound pressure in the room at different points. Lissek explained: "With multiphysics simulation, we can instantly get the frequency distribution in the room with and without the presence of the active absorbers. We can then model the distribution of the sound in the room to learn important parameters such as the modal decay time for the sound to dissipate in the room at its resonance frequencies."

"We can do this all in just ten seconds using the software. We do not need to have acoustic measurements at every point in the space. We can easily map the sound pressure distribution as we move the absorbers to different positions around the room and extrapolate how this changes the sound pressure distribution," Lissek added.

⇨ FINDING THE RIGHT DIRECTIVITY WITH THE RIGHT METASURFACE DESIGN

Many different types of acoustic metasurfaces have been proposed and simulated by Lissek and his team. These include spiral acoustic unit cells, Helmholtz resonators, and active acoustic metasurfaces.

The reflection properties were first set to define individual control laws to assign to each AER unit cell. The identified control settings were then applied to an AER unit cell based on a

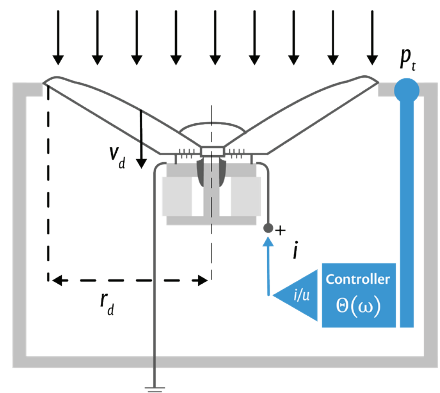

FIGURE 3. Illustration depicting the Active Electroacoustic Resonators (AER) concept.

commercially available "off-the-shelf" electrodynamic loudspeaker in order to experimentally assess the feasibility of the targeted reflection phases along a metasurface of 32 elements (Figure 4). Once the target reflection coefficients were verified, the metasurface was numerically modeled where a full-wave simulation was performed. "The individual elements move like pistons. They are not governed by complex structural dynamics, so we simply assigned the achievable acoustic impedance of each membrane of the model," Lissek explained.

Two cases were simulated with a plane wave background pressure with an incident angle of -45°. The desired angle for the wave reflected over the metasurface was set to 60° and 0°, breaking the Snell-Descartes's law of reflection. The simulation results in Figures 5 and 6 represent the reflected sound pressure level maps over the xz-plane for the two studied angles at f =

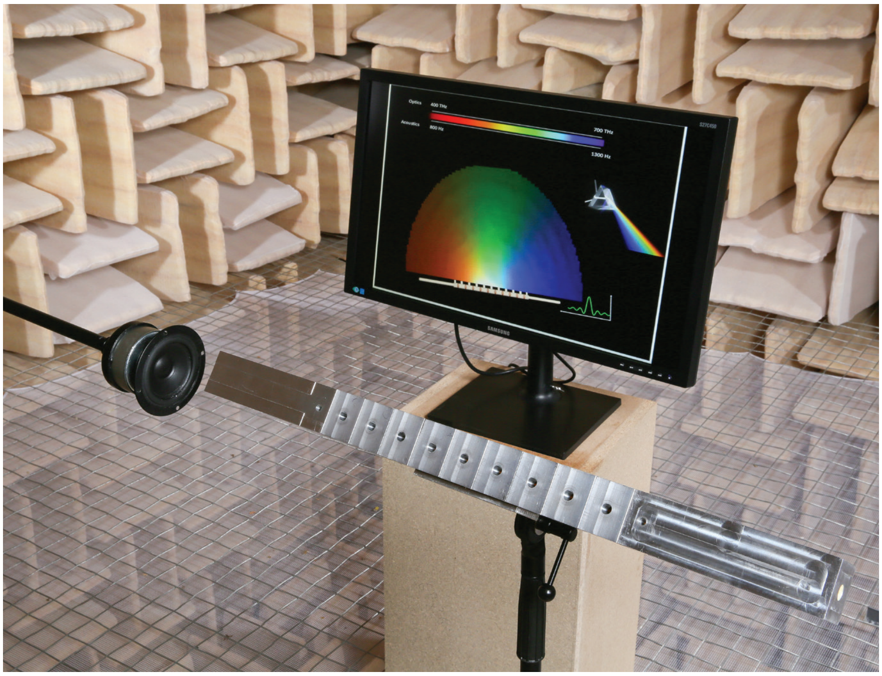

FIGURE 4. Acoustic dispersive prism prototype. Image credit: EPFL/Alain Herzog.

350 Hz. It can be seen that the acoustic impedance imposed on the metasurface unit cells actually allows the wavefronts to be steered toward the prescribed angle.

Figures 5 and 6 demonstrate that there is good agreement between the achieved directivities and the targeted reflected angles, which confirms the effectiveness of the AER to achieve coherent steering over a relatively wide frequency band (almost one octave around 350 Hz). Having shown the effectiveness of the active acoustic metasurfaces over a greater range of frequencies, the researchers were able to further their design and experimental investigations thanks to simulation. Lissek added: "I don't consider myself an expert in FEM modeling. So, one of the greatest benefits for me of COMSOL Multiphysics, is that it provides a simple and user-friendly, yet powerful, set of tools that are easily accessible."

⇨ FURTHERING METASURFACES RESEARCH

The researchers want to move to a full 3D simulation of the acoustic metasurface. Lissek said: "For the purposes of this preliminary research, we used a simplified 1D model (assuming the metasurface has an infinite size towards the y-axis) allowing for faster computation. But a model accounting for the real 2D metasurface in a full 3D acoustic domain should provide more information on the reflected wave properties (e.g., the truncature of the metasurface over the x- and y-axes should increase the directionality of the reflected wave)." They are also integrating lumped circuit modeling into their work to get better insight into the coupling between the acoustic domain and the electrical quantities used in the active control, such as electrical current flowing into the individual AERs. This could also help them develop advanced control strategies; for example, where all the AERs are electrically interconnected.

To further extend their work, Lissek and his team would like to investigate how to integrate such acoustic metasurfaces into a room design. "For example, imagine the possibilities of a theater or a concert hall fitted with acoustic metasurfaces, where the sound reflections can be spatially controlled to create a consistent sound quality. If we could electrically control sound propagation in a room, that would be the Holy Grail for any acoustic professional," Lissek concluded. ❖

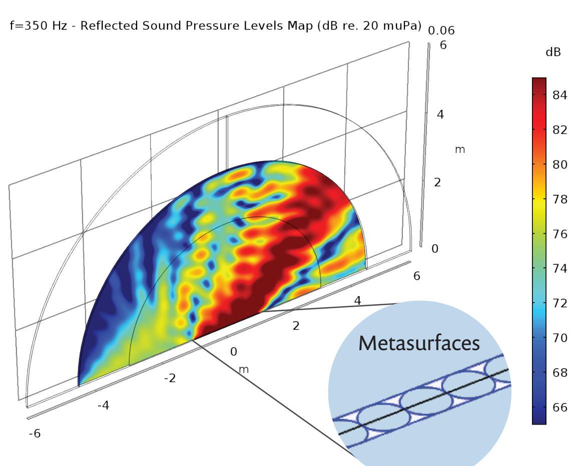

FIGURE 5. Reflected sound pressure levels with 32x32 unit cells at f = 350 Hz, for a prescribed reflected angle of 60°.

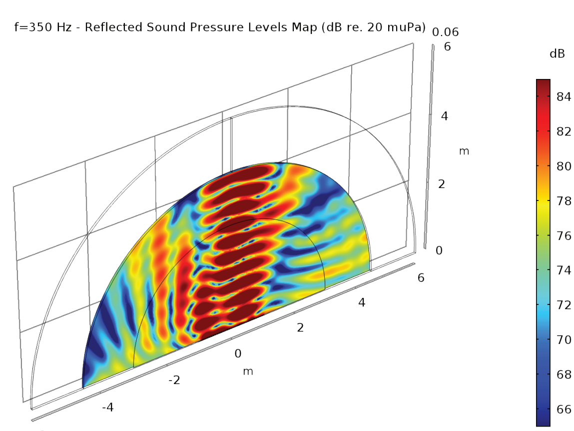

FIGURE 6. Reflected sound pressure levels with 32x32 unit cells, at f = 350 Hz, for a prescribed reflected angle of 0°.