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SPATIAL MODULATION OF ELECTROACOUSTIC RESONATORS FOR PROGRAMMABLE WAVEFRONT CONTROL

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Abstract. *Acoustic metasurfaces composed of subwavelength resonant elements can be classified as passive or active depending on their ability to adapt their properties in real time. Among active solutions, electroacoustic resonators offer a versatile platform, as their target acoustic impedance can be individually programmed through a pressure-based, current-driven control law. This reconfigurability makes them natural candidates for implementing spatially varying boundary conditions without mechanical modification. This work investigates the effect of spatially modulating the control law parameters of an electroacoustic resonator array on the reflected acoustic field. A periodic cosine modulation is applied to the target stiffness along the metasurface, and the resulting scattered field is analyzed using a Bloch–Floquet expansion that predicts the wavenumbers of the generated spatial harmonics. Finite element simulations confirm that the modulation generates harmonics whose propagation angles are governed by the modulation wavenumber, enabling controlled beam splitting away from the specular direction. A trade-off is identified between the angular separation of the harmonics and the range of admissible incidence angles. The results demonstrate programmable wavefront control through spatial modulation of the surface impedance, providing a foundation for the analysis and design of reconfigurable acoustic metasurfaces.*

Keywords: *Active noise control, electroacoustic resonators, metamaterials, acoustic metasurfaces, spatial modulation*

1. INTRODUCTION

Metasurfaces—thin engineered boundaries composed of subwavelength resonant elements—have emerged as a versatile platform for controlling wave propagation beyond the capabilities of conventional homogeneous materials. In optics, Yu *et al.* (2011) introduced the generalized laws of reflection and refraction by imposing a spatially varying phase discontinuity along an interface, demonstrating flexible control of electromagnetic wavefronts based on Fermat’s principle. This concept was subsequently extended to spatiotemporal modulation, where a traveling-wave variation of the surface impedance generates Floquet harmonics that are shifted in both frequency and wavenumber, enabling nonreciprocal scattering and frequency conversion (Hadad *et al.* (2015); Cardin *et al.* (2020)).

The translation of these ideas to acoustics has attracted significant attention. Phase-gradient acoustic metasurfaces have been demonstrated for anomalous reflection and refraction by engineering the local phase response of individual cells (Mei and Wu (2014); Assouar *et al.* (2018)). An alternative strategy consists in introducing a periodic modulation of the surface admittance, which generates Floquet harmonics whose wavenumbers are shifted by integer multiples of the modulation wavenumber β , thereby distributing the scattered energy over multiple propagating harmonics. Kang and Haberman (2022) modulated the surface admittance of a diffuser in space and time to improve sound diffusion. Latter, the authors also proposed to achieve tunable, nonreciprocal scattering from flat metasurfaces (Kang and Haberman (2025)). The use of active metasurfaces for acoustic field shaping extends to applications such as the control of room reverberation (Ma *et al.* (2018)) and efficient nonreciprocal mode transitions using a spatiotemporally modulated membrane (Chen *et al.* (2021)).

Electroacoustic resonators constitute a particularly attractive platform for implementing such programmable boundaries. Rivet *et al.* (2017) proposed a feedforward control architecture that imposes a target acoustic impedance on a loudspeaker diaphragm based on collocated pressure measurements, enabling broadband, low-frequency absorption. Several studies have since evaluated the performance, stability, and limitations of these devices (Karkar *et al.* (2019); De Bono



et al. (2022); Morell *et al.* (2024); Ferreira *et al.* (2026)). In an array of resonators, each resonator can be independently tuned via its own control law, making these devices a natural candidate for spatial modulation of boundary properties. Lissek *et al.* (2018) exploited this tunability by applying a linear phase gradient across an electroacoustic resonators array to steer reflected beams via the generalized Snell's law.

In this work, we investigate the spatial modulation of the target impedance of an electroacoustic resonator-based metasurface using Bloch–Floquet theory. Rather than imposing a linear phase gradient, we consider a periodic cosine modulation of the stiffness parameter along the metasurface, which generates spatial harmonics whose propagation angles are determined by the modulation wavenumber. The resulting scattered field is studied numerically for different incidence angles and modulation parameters, demonstrating that the reflection pattern can be controlled through the modulation wavenumber.

The paper is organized as follows. Section 2 provides the theoretical framework for the scattered field induced by the spatially modulated metasurface, including the Bloch–Floquet expansion and the electroacoustic resonator model. Section 3 describes the numerical model used to simulate the metasurface behavior. Section 4 presents the results for reflection control under different configurations. Finally, Section 5 summarizes the findings and outlines perspectives for future work, including the extension to spatiotemporal modulation and experimental validation.

2. Theoretical background

2.1 Spatial modulation

Consider a metasurface at $z = 0$ with spatially periodic acoustic impedance $Z(x)$ modulated along x with spatial frequency β , as illustrated in Fig. 1(a). Its effect on the half-space it bounds can be expressed using a Bloch–Floquet expansion as the superposition of the incident field $p_i(x, z, t)$ and the scattered field $p_s(x, z, t)$:

$$p(x, z, t) = p_i(x, z, t) + p_s(x, z, t) = p_0 e^{j(\omega_0 t - k_x x + k_z z)} + \sum_{n=-\infty}^{\infty} p_n^r e^{j(\omega_0 t - k_{x_n} x - k_{z_n} z)}, \quad (1)$$

where p_n^r denotes the amplitude of the n -th spatial harmonic introduced in the reflected field by the periodicity of the modulation, and k_{x_n} and k_{z_n} are the spatial harmonic wavenumbers. The wavenumber in the x -direction can be calculated using the continuity of phase in the metasurface

$$k_{x_n} = k_x + n\beta. \quad (2)$$

k_{z_n} follows from the dispersion relation

$$k_{z_n} = \sqrt{(\omega_0/c)^2 - k_{x_n}^2} \quad (3)$$

and discern propagating from evanescent modes. The coefficients p_n^r are determined by enforcing Euler's equation and the impedance boundary condition at $z = 0$ (Hadad *et al.* (2015)).

2.2 Electroacoustic resonators

An electroacoustic resonator as the one shown in Fig. 2a operates on a pressure-based, current-driven control principle. A collocated microphone measures the acoustic pressure at the diaphragm surface, and a controller $H(s)$ computes the electrical current $i(s) = H(s) p_m(s)$ to be injected into the voice coil so as to impose a target specific acoustic impedance, as illustrated in Fig. 2b. Under the assumption of linearity, with small forces imposed by the pressure wavefield and small diaphragm displacements, the force balance on the equivalent lumped-parameter model shown in Fig. 2c yields:

$$M_{ms} \frac{dv(t)}{dt} = S_d p(t) - Bl i(t) - R_{ms} v(t) - \left(\frac{1}{C_{ms}} + \frac{\rho c^2 S_d^2}{V_b} \right) \int v(t) dt, \quad (4)$$

where $v = du/dt$ is the diaphragm velocity, p is the surface pressure at the diaphragm, i is the electrical current flowing through the voice-coil, M_{ms} represents the mass of the driver diaphragm and coil assembly, R_{ms} is the mechanical viscous resistance, S_d is the equivalent area of the driven diaphragm, and Bl is the force factor of the moving coil. K_{mc} is the total mechanical stiffness of the assembled EA, represented as $K_{mc} = 1/C_{ms} + \rho c^2 S_d^2/V_b$, in which C_{ms} is the mechanical compliance of the surrounding suspension and the spider, ρ is the air mass density, c is the speed of sound, V_b is the loudspeaker rear cabinet volume. These mechanical and electrical properties that define the frequency performance of the loudspeaker, i.e., M_{ms} , R_{ms} , K_{mc} , S_d , and Bl , are known as Thiele-Small parameters.

Applying the Laplace transform to the system and defining the concept of mechanical impedance, Z_m , the equation of movement can be expressed as

$$Z_m(s) V(s) = S_d P(s) - Bl I(s), \quad (5)$$

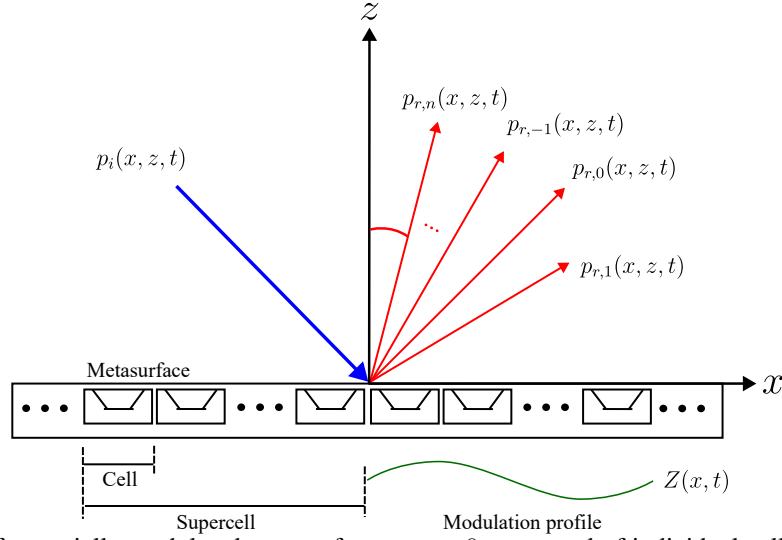


Figure 1: Schematic of a spatially modulated metasurface at $z = 0$ composed of individual cells arranged in a periodic supercell. An incident plane wave $p_i(x, z, t)$ is scattered into multiple Floquet harmonics $p_{r,n}(x, z, t)$ propagating at distinct angles determined by the spatial modulation profile $Z(x)$.

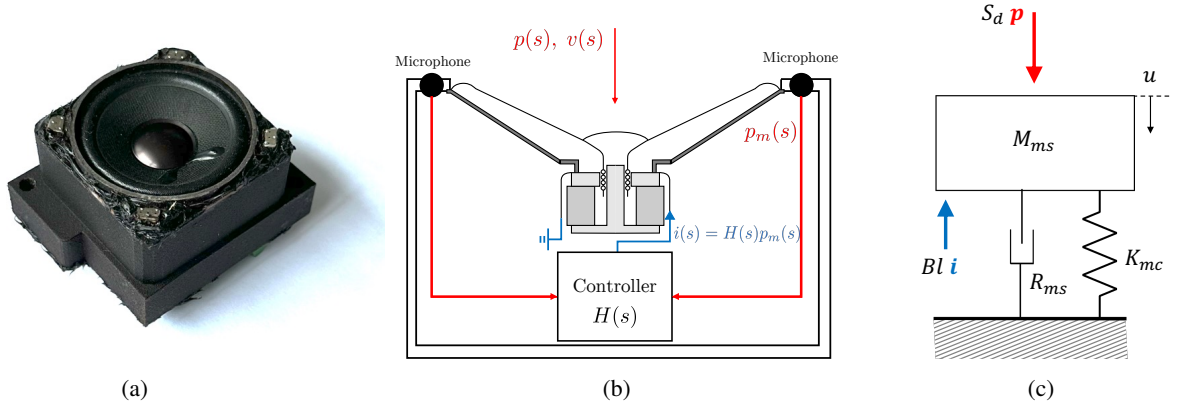


Figure 2: Electroacoustic resonator: (a) Photograph of the physical implementation of an electroacoustic resonator unit cell. (b) Cross-section showing the pressure-based, current-driven control architecture; (c) Equivalent lumped-parameter mechanical model.

where $Z_m(s) = M_{ms}s + R_{ms} + \frac{K_{mc}}{s}$. The control transfer function $H(s)$ relating the imposed current to the measured pressure is defined as

$$H(s) = \frac{I(s)}{P(s)}. \quad (6)$$

It was shown in Rivet *et al.* (2017) that the control law imposing a target specific acoustic impedance Z_{at} on the resonator can be expressed as

$$H(s) = \frac{S_d}{Bl} \left(1 - \frac{Z_{a0}(s)}{Z_{at}(s)} \right), \quad (7)$$

where $Z_{a0} = Z_m(s)/S_d$ is the specific acoustic impedance of the resonator in open circuit. Describing the target as a single-degree-of-freedom (1-DOF) system, it takes the form

$$Z_{at}(s) = \mu_m \frac{M_{ms}}{S_d} s + \mu_r' \frac{R_{ms}}{S_d} + \mu_k \frac{K_{mc}}{S_d} \frac{1}{s}, \quad (8)$$

where μ_m , μ_r' , and μ_k are dimensionless control parameters that adjust the effective mass, resistance, and stiffness of the resonator (Billon *et al.* (2022)). The resistive term $\mu_r' R_{ms}/S_d$ is often expressed as a fraction of the characteristic specific acoustic impedance of air, $\mu_r \rho_0 c_0$. Therefore, the acoustic behavior of an individual cell can be controlled by adapting μ_m , μ_r , and μ_k .

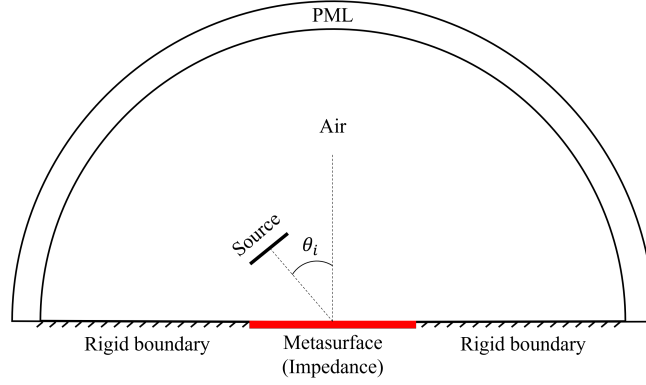


Figure 3: Geometry of the numerical model used to simulate the semi-infinite half-space. The domain is filled with air and bounded by a PML. The lower boundary consists of rigid walls and a central region (red) where the metasurface impedance boundary condition is applied. The source is an internal velocity boundary oriented at an incidence angle θ_i .

Considering an array of electroacoustic resonators whose target parameters vary along the metasurface, i.e. $M_{at}(x) = \mu_m(x) M_{ms}/S_d$, $R_{at}(x) = \mu_r(x) \rho_0 c_0$, and $K_{at}(x) = \mu_k(x) K_{mc}/S_d$, the target impedance of Eq. (8) can be written in the time domain as

$$Z_{at}(x, t) = M_{at}(x) \partial_t v(x, t) + R_{at}(x) v(x, t) + K_{at}(x) \int^t v(x, t') dt'. \quad (9)$$

By enforcing this impedance boundary condition, the spatial harmonics on Eq. (1) can be determined. As an illustration, consider a metasurface with uniform mass and resistance terms and a stiffness modulated by a cosine function:

$$Z_{at}(x, t) = M_{at} \partial_t v(x, t) + R_{at} v(x, t) + K_{at} [1 - m \cos(\beta x)] \int^t v(x, t') dt'. \quad (10)$$

As the cosine modulation can be decomposed as

$$\cos(\beta x) e^{-jk_x x} = \frac{1}{2} [e^{-j(k_x - \beta)x} + e^{-j(k_x + \beta)x}], \quad (11)$$

it generates additional spatial harmonics with wavenumbers

$$k_{x1}^{\pm} = k_x \pm n\beta, \quad (12)$$

as the ones described in Eq. (1). The reflected field is therefore split into spatial harmonics: the specular reflection governed by Snell's law and additional beams induced by the modulation. The energy distribution among these harmonics is controlled by the modulation depth m , the incident field wavenumber k_x , and the harmonic order n .

3. NUMERICAL MODEL

A numerical model is implemented in COMSOL Multiphysics® to evaluate the effects of modulation of a metasurface composed of electroacoustic resonators on the reflected wavefield. The domain is defined as a semi-infinite half-space above the metasurface, as shown in Fig. 3. It is simulated as a semicircular region filled with air, surrounded by a perfectly matched layer (PML) that enforces a non-reflecting condition on the curved boundary. Rigid boundary conditions are applied on the outer boundaries of the PML. The flat lower boundary is divided into two regions: rigid walls on the outer portions and a central segment where the metasurface is represented by a specific acoustic impedance boundary condition, relating the surface pressure to the normal velocity through the target impedance $Z_{at}(x)$ defined in Eq. (8).

The mesh is structured in the PML and unstructured in the air domain. Second-order elements are used throughout, with the maximum element size chosen to ensure at least five elements per wavelength at the highest simulated frequency. The excitation is monochromatic, generated by an interior velocity boundary condition with an amplitude of 0.001 m/s. The source length is set to five wavelengths to approximate plane-wave incidence over the metasurface. The incidence angle θ_i is measured from the surface normal to the midline of the source.

This layout is simulated for multiple incident angles and modulation wavenumbers. For each combination of incidence angle and modulation parameters, three configurations are compared: (i) a rigid wall imposed on the metasurface region, (ii) electroacoustic resonators set to a uniform target impedance without spatial modulation, and (iii) the spatially modulated case. The results are exported and post-processed in MATLAB®. All pressure fields are normalized by the maximum pressure obtained in the rigid-wall configuration, so that the effects of the impedance and its spatial modulation can be assessed relative to perfect reflection.

4. RESULTS

A representative electroacoustic resonator is considered, with Thiele–Small parameters measured at 20 °C as reported in Tab. 1 Ferreira *et al.* (2026). The control parameters are set to $\mu_M = 1.0$ and $\mu_R = 0.5$, while μ_K is chosen so that the target stiffness K_{at} in Eq. (10) places the resonance frequency of the controlled resonator at the excitation frequency of 1000 Hz. This corresponds to a wavenumber of 18.3 rad/m based on the air properties at 20 °C.

Table 1: Parameters of the electroacoustic resonator unit cell at 20 °C and the corresponding effective parameters.

Thiele–Small parameters			Effective parameters		
M_{ms}	[g]	0.55	M_{at}	[kg/m ²]	0.44
R_{ms}	[kg/s]	0.259	R_{at}	[Pa·s/m]	205.8
K_{mc}	[N/m]	7700	K_{at}	[Pa/m]	1.73×10^7
f_{0cell}	[Hz]	595.5	f_{at}	[Hz]	1000
Physical and environmental parameters					
d	[m]	0.05	ρ_0	[kg/m ³]	1.2
S_d	[m ²]	0.0025	c_0	[m/s]	343

The metasurface is composed of N identical cells of length $d = 50$ mm arranged in a periodic supercell, so that the modulation wavenumber is $\beta = 2\pi/(Nd)$. Three supercell lengths are considered, $N = 20, 30$, and 40 , corresponding to modulation wavenumbers of $\beta = 6.28, 4.19$, and 3.14 rad/m, respectively. A cosine modulation with wavenumber β is applied to the stiffness parameter along the metasurface according to Eq. (10). Figure 4a illustrates the resulting spatial modulation profile for $N = 20$ and several values of the modulation depth m . Because only the stiffness term is modulated, the local resonance frequency of each cell varies along the surface as shown in Fig. 4b. The relationship between stiffness and resonance frequency, $f_{at} = (1/2\pi)\sqrt{K_{at}/M_{at}}$, is nonlinear, so that a symmetric cosine variation in K_{at} produces an asymmetric distribution of f_{at} about the unmodulated target frequency, particularly at larger modulation values.

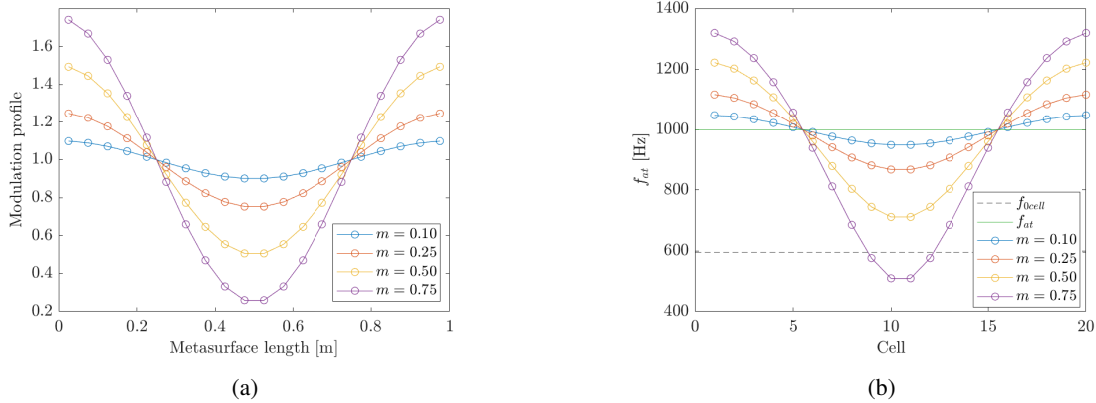


Figure 4: Effect of the modulation depth m on the properties of the metasurface for a supercell of $N = 20$ cells. (a) Spatial modulation profile $[1 - m \cos(\beta x)]$ applied to the target stiffness along the metasurface length. (b) Resulting local resonance frequency f_{at} of each cell.

A modulation depth of $m = 0.5$ is selected to evaluate the effect of the presence of the metasurface. Figure 5 presents the simulated pressure field (top row) and the corresponding two-dimensional wavenumber spectrum (bottom row) for the three metasurface configurations at an incidence angle of $\theta_i = 30^\circ$ and $f = 1000$ Hz. The wavenumber spectrum is estimated from a two-dimensional fast Fourier transform (2D-FFT) applied to the x -positive region of the half-plane, using a 2D Hanning window with 50% overlap. The amplitude of the Fourier transform is normalized using the maximum values obtained at the rigid-wall analysis.

For the rigid wall case, shown in Fig. 5a, the reflected field is purely specular. The wavenumber spectrum exhibits a single energy concentration centered on the fundamental wavenumber pair $(k_x, k_z) = (9.16, 15.87)$ rad/m, consistent with specular reflection at $\theta_r = 30^\circ$. When the electroacoustic resonators are introduced with a uniform target impedance and no spatial modulation, as in Fig. 5b, the surface absorbs part of the incident wave, reducing the overall amplitude of the reflected field, but the reflection remains specular. No additional spatial harmonics are generated, which is consistent with the Generalized Snell's law for a homogeneous impedance boundary.

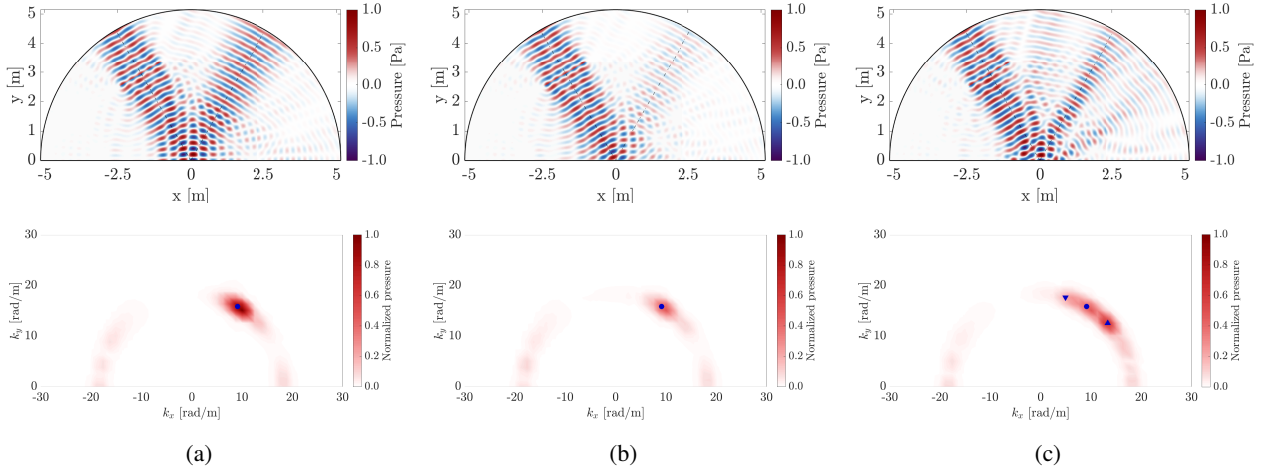


Figure 5: Comparison of the pressure field (top) and wavenumber spectrum (bottom) for the three metasurface configurations $\theta_i = 30^\circ$: (a) rigid wall; (b) unmodulated metasurface; and (c) spatially modulated metasurface ($N = 30$, $m = 0.5$). Markers indicate: (●) specular harmonic $n = 0$, (▲) $n = +1$ harmonic, and (■) $n = -1$ harmonic.

When a cosine modulation is applied to the metasurface ($N = 30$, $m = 0.5$), as shown in Fig. 5c, additional spatial harmonics appear in the wavenumber spectrum. The majority of the reflected energy is distributed around three wavenumber pairs: the specular component at $(k_{x_0}, k_{z_0}) = (9.16, 15.87)$ rad/m, the $n = -1$ harmonic at $(k_{x_{-1}}, k_{z_{-1}}) = (4.97, 17.63)$ rad/m, and the $n = +1$ harmonic at $(k_{x_{+1}}, k_{z_{+1}}) = (13.35, 12.79)$ rad/m, in agreement with the values predicted by the Bloch–Floquet expansion in Eq. (12) and reported in Tab. 2. The pressure field confirms this splitting, with three distinct reflected beams propagating at different angles from the surface. It is important to highlight that the energy concentrations in the wavenumber spectra are not confined to discrete points but are spread along the isofrequency arc $k_x^2 + k_z^2 = k_0^2$. This spreading results from the finite extent of the metasurface and the windowed 2D-FFT used for the spectral estimation and occurs even for the rigid wall case, and should not be interpreted as a departure from the theoretical predictions.

Table 2 presents the wavenumber components of the $n = \pm 1$ spatial harmonics for the three supercell sizes and incidence angles considered, with k_{x_n} computed from the phase continuity condition in Eq. (2) and k_{z_n} from the dispersion relation in Eq. (3). A trade-off is observed between beam splitting and the range of admissible incidence angles. A shorter supercell (smaller N , larger β) produces a wider angular separation between the spatial harmonics, but at the cost of pushing the $n = +1$ harmonic beyond the radiation condition ($k_{x_n} > k_0$), rendering it evanescent. This trend is evident in Tab. 2. For $N = 20$, the $n = +1$ harmonic becomes evanescent at $\theta_i = 45^\circ$, whereas for $N = 40$ this occurs only at $\theta_i = 60^\circ$. In practice, this constrains the useful range of incidence angles for a given supercell configuration.

Table 2: Wavenumber components of the incident and scattered fields for three incidence angles at $f = 1000$ Hz ($k_0 = 18.32$ rad/m). The specular component ($n = 0$) is independent of the supercell size N . The $n = \pm 1$ harmonics are computed as $k_{x_n} = k_x + n\beta$, with $\beta = 2\pi/(Nd)$ and $d = 50$ mm. Evanescent harmonics are marked with an *.

θ_i [deg]	k_x [rad/m]	k_z [rad/m]	θ_0 [deg]
30	9.16	15.87	30.0
45	12.95	12.95	45.0
60	15.87	9.16	60.0

θ_i [deg]	n	$N = 20$ $\beta = 6.28$		$N = 30$ $\beta = 4.19$		$N = 40$ $\beta = 3.14$	
		k_{x_n}	θ_n	k_{x_n}	θ_n	k_{x_n}	θ_n
		[rad/m]	[deg]	[rad/m]	[deg]	[rad/m]	[deg]
30	-1	2.88	9.0	4.97	15.7	6.02	19.2
	+1	15.44	57.4	13.35	46.7	12.30	42.2
45	-1	6.67	21.3	8.76	28.6	9.81	32.4
	+1	19.23*	—	17.14	69.2	16.09	61.5
60	-1	9.59	31.5	11.68	39.6	12.72	44.0
	+1	22.15*	—	20.06*	—	19.01*	—

Figure 6 presents the pressure field and wavenumber spectrum for the nine combinations of supercell size ($N = 20, 30, 40$) and incidence angle ($\theta_i = 30^\circ, 45^\circ, 60^\circ$) with $m = 0.5$.

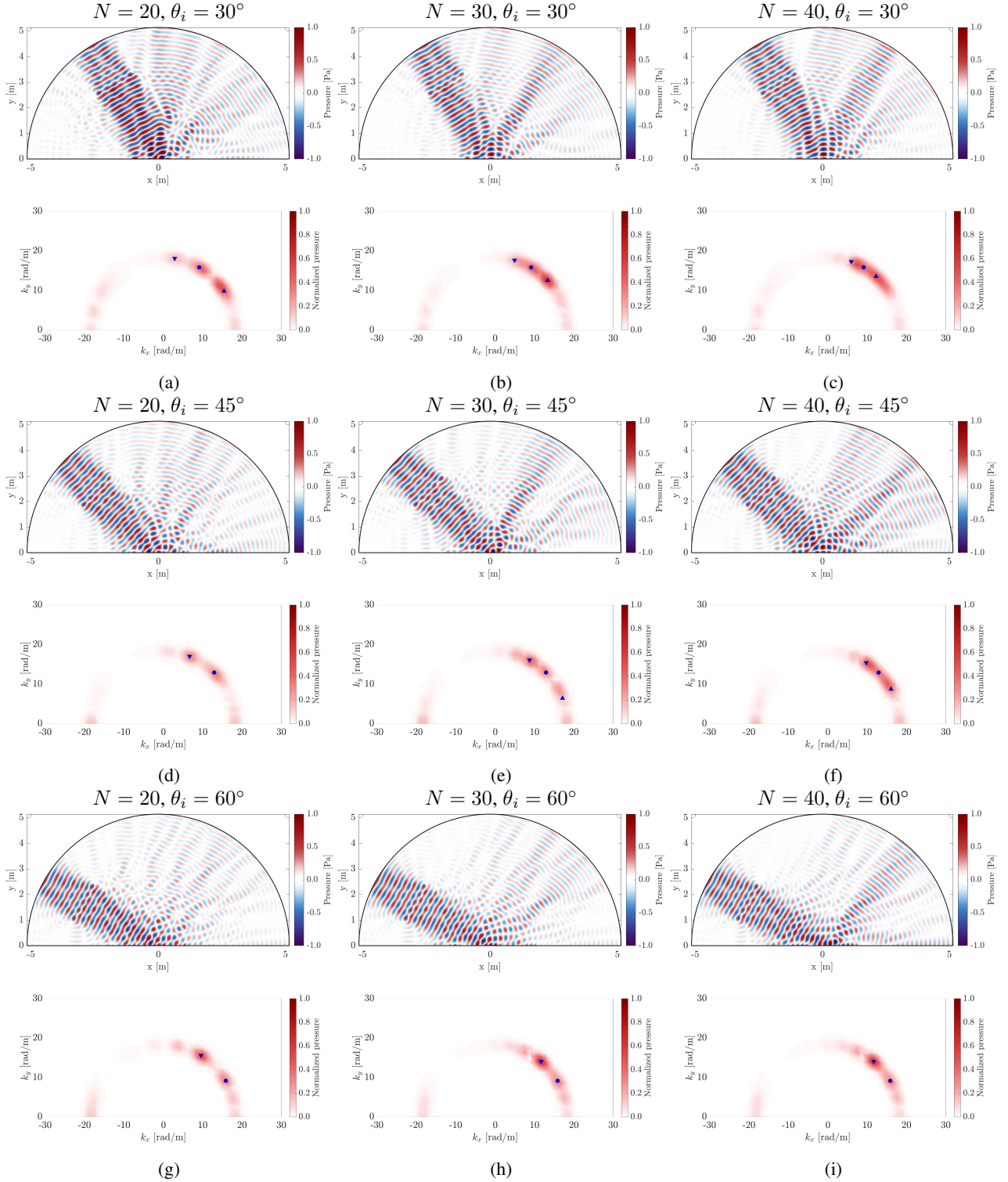


Figure 6: Pressure (up) and wavenumber (bottom) distribution comparison for different incidence angles and modulation wavenumber under a 1000 Hz plane wave incident at $30^\circ, 45^\circ$, and 60° . The modulation consists of 20, 30, and 40 cells per spatial period, and $m = 0.50$. Markers indicate: (●) specular harmonic $n = 0$, (▲) $n = +1$ harmonic, and (■) $n = -1$ harmonic.

Several trends are observed. First, reading each column from top to bottom (increasing θ_i at fixed N), the $n = +1$ harmonic progressively approaches and eventually exceeds the radiation limit $k_{x_n} = k_0$, becoming evanescent. This

occurs earliest for the shortest supercell ($N = 20$), where the $n = +1$ harmonic is already evanescent at $\theta_i = 45^\circ$ (Fig. 6d), whereas for $N = 40$ the three harmonics remain propagating up to $\theta_i = 45^\circ$ (Fig. 6f). At $\theta_i = 60^\circ$, the $n = +1$ harmonic is evanescent for all three supercell sizes (Figs. 6g–i), consistent with the predictions in Tab. 2.

Second, the energy distribution among the propagating harmonics depends strongly on the combination of N and θ_i . For $N = 40$ at $\theta_i = 45^\circ$ (Fig. 6f), the $n = \pm 1$ harmonics are approximately symmetric about the specular component, resulting in a nearly balanced three-beam pattern. In contrast, at $\theta_i = 60^\circ$ with the same supercell (Fig. 6i), the evanescence of the $n = +1$ harmonic redirects energy toward the $n = -1$ harmonic, which becomes the dominant reflected component and effectively shifts the principal reflection angle away from the specular direction. A similar redistribution is observed for $N = 30$ at $\theta_i = 60^\circ$ (Fig. 6h). Third, reading each row from left to right (increasing N at fixed θ_i), the angular separation between the harmonics narrows as β decreases, and the three reflected beams converge toward the specular direction, which is consistent with the smaller wavenumber shift $\pm\beta$ applied to each harmonic.

Furthermore, even when both $n = \pm 1$ harmonics propagate, their amplitudes are not equal. This asymmetry is particularly visible at $\theta_i = 30^\circ$ (Figs. 6a–c), where the $n = -1$ harmonic consistently carries less energy than the $n = +1$ harmonic. This behavior is consistent with the nonlinear relationship between stiffness and resonance frequency. A symmetric cosine modulation of K_{at} does not produce a symmetric impedance variation about the target frequency (Fig. 4b), which results in unequal coupling strengths to the $n = +1$ and $n = -1$ spatial harmonics. A detailed analytical characterization of this amplitude asymmetry requires the full harmonic balance solution, which is left for future work.

5. FINAL REMARKS

This work demonstrated that spatial modulation of the target impedance of an electroacoustic resonator-based metasurface enables programmable control of the reflected wavefront. A cosine modulation of the stiffness parameter generates spatial harmonics whose propagation angles are set by the modulation wavenumber β , as confirmed by Bloch–Floquet theory and finite element simulations. A trade-off was identified between angular separation and the range of admissible incidence angles, and an amplitude asymmetry between harmonics was linked to the nonlinear stiffness–frequency relationship.

Future work will address the influence of the modulation depth on the energy distribution among harmonics, the role of the ratio between acoustic and modulation wavelengths in activating higher-order modes, and the effect of spatial discretization on the fidelity of the prescribed impedance profile. The extension to spatiotemporal modulation and experimental validation are also planned.

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