

Acoustic Metamaterials in Printed Photopolymers: Resonance, Damping, Manufacturing Variation and Band-Gap Verification

Qualifying wave-control performance by measured geometry, loss, boundary conditions and experimentally demonstrated attenuation bands

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Abstract

Printed acoustic metamaterials can show strong attenuation or band-gap behaviour only when resonator geometry, damping, specimen length and boundary conditions remain inside the intended regime. ER-366 links transfer-function or insertion-loss measurements to laser-vibrometric or pressure-field maps, CT metrology and frequency-dependent constituent properties. Cell-count sweeps distinguish bulk behaviour from sample-boundary modes, while temperature and deliberate geometric perturbations expose damping and manufacturing sensitivity. The qualification problem is therefore expressed as a guaranteed frequency interval and attenuation level under stated variation, together with evidence that identifies whether local resonance, Bragg scattering or boundary artifacts control the measured response.

Keywords: acoustic metamaterial; band gap; resonance; damping; manufacturing variation; photopolymer

1. Qualification problem: acoustic metamaterials

Qualification of acoustic metamaterials requires more than matching nominal process settings. The analysis distinguishes frequency band guaranteed under manufacturing variation, minimum number of cells for specified attenuation, and whether local resonance or Bragg mechanism better fits bandwidth and size constraints, and uses normalised frequency $f a/c$, loss factor or damping, and geometric coefficient of variation to show whether the underlying state is comparable. [1,3]

1.1 Scope boundary.

ER-366 owns acoustic metamaterials printed in photopolymers, including resonance, damping, manufacturing variation and band-gap verification. ER-361 owns general mechanical metamaterials and ER-367 thermal metamaterials; this article treats wave-acoustic response rather than static stiffness or heat-flow shaping.

2. Governing balances for acoustic metamaterials

Acoustic band behaviour is framed by relations for scaled frequency, dissipation, and manufacturing variation.

Bragg band gaps scale with periodic spacing relative to wavelength whereas local-resonance gaps depend on resonator mass and stiffness

*resonance frequency scales approximately with $\sqrt{k/m}$, making thin-feature error disproportionately important
damping controls attenuation bandwidth and peak transmissibility*

The scaled variables distinguish resonance placement, damping-controlled attenuation, and geometry-induced band uncertainty.

3. Regime boundaries for acoustic metamaterials

For acoustic metamaterials, Table 1 determines whether bandwidth, cell count, or mechanism choice is most sensitive to the tested regime.

Table 1. Regime indicators for acoustic-metamaterial response.

Indicator	Engineering meaning	Use
normalised frequency $f a/c$	frequency scaled by cell size a and wave speed c	Partition the evidence for 'frequency band guaranteed under manufacturing variation' by normalised frequency $f a/c$; this indicator identifies where changes in frequency scaled by cell size a and wave speed c make the reference state unrepresentative.
loss factor or damping	dimensionless dissipation governing attenuation around resonant response	Partition the evidence for 'minimum number of cells for specified attenuation' by loss factor or damping; this indicator identifies where changes in dimensionless dissipation governing attenuation around resonant response make the reference state unrepresentative.
geometric coefficient of variation	manufacturing variation scaled to resonator gap or thickness	Partition the evidence for 'whether local resonance or Bragg mechanism better fits bandwidth and size constraints' by geometric coefficient of variation; this indicator identifies where changes in manufacturing variation scaled to resonator gap or thickness make the reference state unrepresentative.

Attenuation claims are restricted to the sampled frequency, loss, and manufacturing-variation space.

4. Couplings that move the acoustic metamaterials

Photopolymer modulus and loss factor are frequency- and temperature-dependent.

Overcure shifts neck/cavity dimensions and therefore resonance.

Boundary mounting can create apparent stop bands unrelated to bulk periodicity.

5. Failure signatures and false diagnoses

For this review, rejection is organised around band-gap shift outside target range, leakage paths from incomplete walls and excess damping that suppresses resonant contrast. The three measurements transfer-function or insertion-loss spectra, laser vibrometry or scanning pressure fields and CT dimensional metrology of resonators/channels are retained because each supplies information that the others cannot provide. Mechanism attribution follows the complete Table 2 response vector; a single matching row cannot override contradictory evidence elsewhere in the matrix.

Table 2. Failure-mode discrimination for acoustic-metamaterial response.

Failure mode	Observable signature	Discriminating evidence
band-gap shift outside target range	transfer-function or insertion-loss spectra	specimen length/cell-count sweep to separate boundary effects
leakage paths from incomplete walls	laser vibrometry or scanning pressure fields	temperature sweep at fixed geometry
excess damping that suppresses resonant contrast	CT dimensional metrology of resonators/channels	controlled geometric perturbations/disorder
sample-boundary modes mistaken for metamaterial response	DMA for frequency-dependent constituent properties	multiple mounting conditions

6. Measuring acoustic metamaterials with traceable uncertainty

For qualification, the three Table 2 observables are acquired as distinct evidence streams with their own calibration and repeatability records. The working sequence for acoustic metamaterials has three parts: independent resolution of Bragg scaling and local resonance; an uncertainty-controlled perturbation of damping; and separate monitoring of geometric tolerance; during metrology of acoustic metamaterials, damping is resolved against geometric tolerance. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; the uncertainty record for acoustic metamaterials keeps geometric tolerance separate from Bragg scaling.

7. Experiments that discriminate competing mechanisms

The intervention set in Table 2 is intentionally orthogonal. Each experiment is retained because it changes the ranking of plausible mechanisms. Three independent checks structure the acoustic metamaterials assessment; during the causal challenge for acoustic metamaterials, geometric tolerance is tested against Bragg scaling. A causal contrast between bragg scaling and damping establishes the primary state, a replicate test of geometric tolerance tests whether that state survives transfer, and a boundary challenge involving local resonance is the perturbation used when the two disagree; the experiment for acoustic metamaterials separates Bragg scaling from local resonance.

8. Model identification and validation for acoustic metamaterials

A three-way evidence split is used: one Table 2 branch constrains parameters, one checks transfer, and one tests whether the parameterisation is unique enough for qualification. [1,3] [5] [2,4] Decision confidence is carried separately to the three Table 3 boundaries so that evidence strength remains visible. For the acoustic metamaterials problem, an uncertainty-bounded check on geometric tolerance defines the independent cross-check rather than a tuning variable; within model identification for acoustic metamaterials, Bragg scaling is not fitted through local resonance. The main inference uses parameter estimation for Bragg scaling and local resonance, whereas prediction against damping is reserved for the boundary test that can overturn the proposed interpretation; prediction for acoustic metamaterials keeps local resonance independent of damping.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for acoustic-metamaterial response.

Decision	Minimum evidence	Acceptance logic
frequency band guaranteed under manufacturing variation	Justify frequency band guaranteed under manufacturing variation using repeated transfer-function or insertion-loss spectra measurements across the claimed range and a documented decision uncertainty at the limiting condition.	Acceptance follows when 'specimen length/cell-count sweep to separate boundary effects' leaves the measured transfer-function or insertion-loss spectra relationship intact and no transition toward band-gap shift outside target range is detected.
minimum number of cells for specified attenuation	For minimum number of cells for specified attenuation, collect laser vibrometry or scanning pressure fields in matched reference/candidate tests and repeat the condition nearest the acceptance boundary.	Retain the decision only while 'temperature sweep at fixed geometry' keeps laser vibrometry or scanning pressure fields within the tested envelope; observation of leakage paths from incomplete walls terminates the claim.
whether local resonance or Bragg mechanism better fits bandwidth and size constraints	A decision on whether local resonance or Bragg mechanism better fits bandwidth and size constraints requires CT dimensional metrology of resonators/channels data across the transfer range, including a boundary case and a replicate series that demonstrates stability.	The qualified decision holds when 'controlled geometric perturbations/disorder' does not move CT dimensional metrology of resonators/channels beyond the measured boundary and does not trigger excess damping that suppresses resonant contrast.

Rather than reduce acoustic metamaterials to one surrogate, the analysis combines an explicit transfer limit on geometric tolerance with tested ranges in Bragg scaling and local resonance; inside the acoustic metamaterials envelope, local resonance and damping define different transfer limits. A separate a separate boundary for damping is used to challenge that interpretation, making disagreement between the two routes visible instead of averaging it away; qualification of acoustic metamaterials bounds damping separately from geometric tolerance.

10. Design consequences for acoustic metamaterials

For implementation control, a design change governed by Bragg scaling is adjusted against an implementation check on damping while minimum number of cells for specified attenuation is controlled independently; a material shift in a requalification trigger tied to geometric tolerance is treated as a new case; during design implementation for acoustic metamaterials, damping is constrained by geometric tolerance. This arrangement keeps the implementation traceable when acoustic metamaterials changes with scale or duty history; the acoustic metamaterials design record separates geometric tolerance from Bragg scaling.

11. Evidence gaps for acoustic metamaterials

Evidence for acoustic metamaterials is not accepted from a single nominal condition; for unresolved acoustic metamaterials transfer, geometric tolerance is studied separately from Bragg scaling. The analysis requires scale transfer of Bragg scaling, follows it with independent replication of geometric tolerance, and uses uncertainty in local resonance versus damping as a targeted challenge wherever the two indicate different mechanism or margin; the evidence gap in acoustic metamaterials distinguishes Bragg scaling from local resonance.

12. Qualification outcome for acoustic metamaterials

Qualification is closed only under conditions represented by all three Table 3 rows. A changed state variable reopens the relevant limit. Causal evidence that separates local resonance from damping is the first stress test for acoustic metamaterials; only after that result is bounded is agreement between measurement and prediction for Bragg scaling interpreted; at final qualification of acoustic metamaterials, Bragg scaling is reconciled with local resonance. The record keeps a renewed-evidence trigger when geometric tolerance changes outside that inference and reports it as an independent line of evidence; the closing acoustic metamaterials claim keeps local resonance distinct from damping.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.