# Numerical Analysis of Vibroacoustic Loads on Composite Payload Fairings of Launch Vehicles: A Review of Methods and Approaches

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**Abstract**

The paper surveys numerical practices used to predict and mitigate vibroacoustic loads inside composite payload fairings across liftoff and early ascent. Novelty lies in a unified mapping between exterior-source solvers and interior structure–cavity models, linking unsteady RANS for launch-pad environments with FE–SEA backbones, transfer-matrix screening for multilayer curved shells, and FE–BEM spot checks. The review compares transmission-control options suitable for composite structures, including locally resonant liners, partial porous fills, micro-perforated hierarchical sandwiches, and high-intensity nonlinear stacks, against mass and manufacturability constraints.

Special attention is given to deflector-induced source shaping, coherence-preserving load transfer, and parameter identification for blanket and liner impedances. The objective is to distill a staged workflow that reconciles accuracy with design-cycle cost while sustaining qualification margins for avionics. Methods include comparative synthesis, model-taxonomy analysis, and normalization of reported vibroacoustic metrics to one-third-octave SPL and transmission loss.

Because vibroacoustic qualification margins are mission-critical for launch vehicles, and because composite fairings represent an area of engineering central to the aerospace sector, these modeling strategies support industry reliability in advanced structural–acoustic design.

Keywords: vibroacoustics, payload fairing, launch vehicle, composite sandwich shells, FE–SEA, URANS, FE–BEM coupling, transfer-matrix method, micro-perforated panels, resonant liners.



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## 1. Introduction

Launch environments expose payload fairings to broadband exterior fields whose spectral content and spatial coherence shift from the liftoff plateau to transonic regime. Composite fairings respond through coupled structural–acoustic mechanisms, making credible prediction dependent on consistent transfer of validated exterior loads to interior solvers and on treatment strategies compatible with composite manufacturing window.

The aim of this review is to synthesize recent computational developments into a practical, qualification-oriented framework able to support fairing design decisions under strict mass, cost, and schedule constraints. The study addresses three tasks:

1) Compare exterior and interior numerical workflows across mission phases and frequency bands, with emphasis on spectra and coherence transfer.

2) Synthesize transmission-control and absorption options suitable for composite shells, assessing trade-offs among attenuation, added mass, and manufacturability.

3) Formulate a staged, verification-ready workflow aligning rapid design sweeps with high-fidelity confirmation and parameter identification.

Novelty arises from integrating regime-segmented source prediction, hybrid interior modeling, and composite-compatible acoustic packages into an operational sequence aimed at producing qualification-credible SPL predictions. Such modeling frameworks align with the broader engineering needs of aerospace programs, both governmental and commercial, supporting innovation in launch vehicle technology.

## 2. Materials and Methods

The synthesis relies on peer-reviewed studies published between 2022 and 2024 and one NASA technical report. These works span exterior-source prediction, interior FE–SEA and FE–BEM coupling, transmission-loss analytics for curved composite shells, and contemporary acoustic package design.

The principal contributions are:

- FE–SEA integration for full-scale fairings – Ahn [1]
- URANS liftoff fields and deflector sensitivity – Escartí-Guillem [2–4]
- Composite fairing structural parameters – Lee [5]
- Locally resonant liners – Chimeno Manguán [6]
- Transfer-matrix method for multilayer curved shells – Parrinello [7]
- Blanket fill trade modeling (NASA) – Shearer [8]
- Micro-perforated hierarchical sandwiches – Zhou [9]
- Nonlinear multilayer absorbers – Zhu [10]

Comparative method and structured content analysis were applied to extract modeling assumptions, coupling protocols, and reported metrics. Results were normalized to one-third-octave spectra and transmission-loss metrics wherever feasible. A model-taxonomy mapping linked regime-specific exterior solvers to interior FE–SEA/FE–BEM hybrid and semi-analytical methods.

## 3. Results

Recent studies converge on the conclusion that interior acoustic fields in composite fairings are driven by broadband excitations whose spectral content shifts significantly between liftoff and transonic ascent. Multi-regime modeling is therefore essential, requiring validated exterior predictions coherently mapped into structural–acoustic solvers.

Unsteady RANS (URANS) simulations calibrated on launch-pad configurations reproduce the impinging-jet and deflector-induced wave systems that dominate liftoff acoustics. When the resulting wall-pressure statistics from these runs are transferred to interior FE–SEA or FE–BEM models, predicted one-third-octave spectra align with measured envelopes and replicate sensitivity to fairing diameter and deflector-geometry sensitivities [2–4]. These findings confirm that exterior source modeling quality is a first-order driver of credible interior load predictions and that deflector design choices can reduce the incident energy reaching the fairing without adverse plume-flow penalties [3; 4].

For interior prediction over the full octave span of interest under tight computational budgets, hybrid frequency-domain workflows that blend deterministic FE with high-frequency Statistical Energy Analysis remain today's most practical route. The FE–SEA method reported for a full-scale fairing shows stable energy partition across structural and acoustic subsystems, captures blanket and resonator treatments as parametric subsystems, and reproduces spatial variance trends inside the enclosure that pure FE would only resolve at prohibitive cost [1].

In parallel, semi-analytical transfer-matrix formulations for baffled multilayer curved shells provide fast and physically transparent estimates of transmission loss for cylindrical sandwich sections with poroelastic layers;

when these are cross-checked against FE–BEM baselines, errors remain bounded while runtime drops by orders of magnitude, which is crucial for design space exploration of laminate stacks and acoustic packagTheser, these packages. These two lines of work supply a numerically efficient backbone to sweep composite layups, core densities, and surface treatments before refining finalists with fully coupled FE–BEM in bands with structural-acoustic modal crowding.

Material and construction choices in composite fairings affect both structure-borne and air-borne pathways. A recent glass-fabric composite fairing program quantified stiffness-to-mass gains and manufacturing tolerances achievable with RTM, clarifying the usable damping window and panel curvature limits that underpin subsequent acoustic models [5]. On the transmission side, micro-perforated and hierarchical honeycomb cores deliver broadband absorption at low areal mass when tuned for resonant–viscous synergy; micro-perforated sandwich panels with hierarchical cores extend the absorption to lower bands without sacrificing structural integrity, offering attractive trade-offs for panels that must remain load-bearing [9]. Under high-intensity excitation, multilayer dissipative stacks exhibit beneficial nonlinearity: vortex-dominated flow in sub-slits increases effective resistance with SPL, raising in-situ absorption in the 140 dB environment characteristic of ascent, with reverberant-chamber and scaled-fairing tests confirming reductions in average internal levels beyond what linear models would predict [10].

Treatments that target the interior cavity directly (blankets, resonators, and locally resonant liners) show complementary benefits when mapped onto the spatial wavenumber content of the field predicted by FE–SEA. A locally resonant liner tailored to liftoff spectra increases attenuation in critical one-third-octaves while keeping mass within payload-interface limits; numerical and prototyping evidence demonstrate meaningful Sound Pressure Level (SPL) depressions at sensor locations representative of avionics items [6]. Helmholtz-type and distributed-resonator packages modeled within FE–SEA similarly shift energy away from structural modes most responsible for payload response, and sensitivity analyses identify tuning bandwidths tolerant to manufacturing scatter typical for flight blankets [1; 6].

Figure 1 illustrates the canonical multilayer curved-shell representation used to compute transmission loss and to place treatments at acoustically efficient radii; in practice, this geometry links directly to the axial-circumferential modal basis used by both FE–SEA and transfer-matrix solvers and clarifies how additional poroelastic or micro-perforated layers alter impedance matching at the fluid–structure boundaries [7].

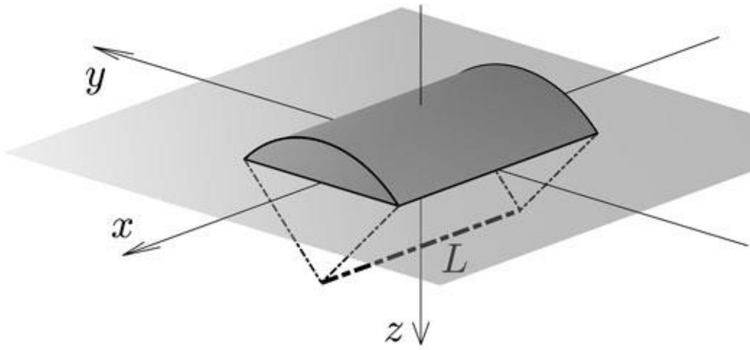


Fig. 1. Multilayer curved-shell model of a baffled cylindrical section used to compute transmission loss and to embed poroelastic and resonant layers

Blanket fill fraction and placement within the enclosure persist as high-leverage design knobs. NASA's fill-effect modeling indicates that partial fill can outperform naïve "more is better" strategies by mitigating modal coloration and avoiding over-damping of beneficial diffusion pathways; the study provides a practical map between percent fill, blanket flow resistivity, and expected SPL reduction at accelerometer locations representative of payload primary structure [8]. When combined with deflector optimization that reduces the exterior energy budget upstream [3; 4], and with resonant liners tuned to liftoff plateaus [6], end-to-end numerical campaigns achieve cumulative interior reductions that reconcile payload qualification limits with mass and cost constraints. In composite builds, these interior interventions interact with laminate-level choices (fibre orientation, core cell size) that set panel radiation efficiency; transfer-matrix analyses for curved shells help decouple the dominant air-borne pathway from structure-borne spillover and identify curvature–layup pairs with favorable transmission minima [7].

The overall numerical evidence supports a staged workflow: predict exterior sources by URANS for liftoff and by wall-pressure models for transonic, pass consistent spectra and spatial coherence to interior solvers, and iterate composite panel and treatment configurations with FE–SEA and transfer-matrix accelerators before high-fidelity FE–BEM spot checks.

This sequencing reproduces the spectrum-shaping impact of deflectors [3], respects fairing-specific constraints on mass and manufacturability [5], and exploits composite-compatible, low-mass absorbers whose performance improves under the high SPLs of ascent [6; 9; 10], all while keeping computational cost commensurate with design timelines.

## 4. Discussion

A coherent interpretation of the numerical evidence requires separating source-generation fidelity from interior prediction economy and then reuniting them through consistent load transfer and verification loops. Exterior computations that resolve the launch-pad jet/deflector system with URANS reproduce the broadband plateaus that dominate early ascent; when pressure statistics from these runs feed interior solvers, the predicted in-fairing spectra reproduce measured envelopes with credible sensitivity to deflector geometry and fairing diameter [2–4]. Interior predictions that must cover sub-kilohertz to multi-kilohertz bands under design-cycle constraints benefit from FE–SEA hybrids, which maintain energy bookkeeping across structural and acoustic subsystems at practical mesh densities while preserving the ability to parametrize blankets, resonators, and liners; the approach reported for a full-scale fairing provides stable energy partitioning that pure FE achieves only at prohibitive cost [1]. Transmission along the air-borne path depends strongly on laminate and curvature choices, and transfer-matrix treatments for multilayer curved shells offer fast, physically transparent transmission-loss estimates suitable for sweeping layups and packages before FE–BEM confirmation in bands with modal crowding [7]. Material choices and acoustic treatments in contemporary composite builds (glass-fabric RTM panels, micro-perforated sandwich panels with hierarchical cores, locally resonant liners, and nonlinear multilayer dissipative stacks) show complementary operating windows and mass footprints that can be coordinated with partial blanket fills to meet payload qualification limits without overshooting mass budgets [5; 6; 8–10]. The discussion below organizes these trade-offs and maps them into actionable modeling choices, while keeping the numbering of sources consistent with the Results section.

The first synthesis concerns regime segmentation. URANS for liftoff delivers robust wall-pressure fields with correct coherence properties when jet–deflector interactions are resolved and boundary conditions reflect the actual flame trench; these fields, once spatially mapped to the fairing exterior, determine much of the interior response at low and mid bands. Transonic portions of ascent require alternative wall-pressure models, but the reviewed liftoff studies already demonstrate that the largest dividends currently come from improving near-ground source modeling and deflector design, not from over-refining interior models [2–4]. When these exterior predictions are coupled to interior FE–SEA or FE–BEM, the load-path clarity improves, revealing where structural radiation efficiency, cavity modal density, and treatment impedance interact destructively or constructively [1; 7].

The second synthesis concerns treatment selection under mass and manufacturability constraints in composite fairings. Locally resonant liners tuned to one-third-octaves characteristic of liftoff provide focused attenuation near avionics-critical bands with controlled mass addition and tunable bandwidth, making them strong first-line options for low-mass builds [6]. Micro-perforated sandwich panels with hierarchical honeycomb cores extend absorption into lower bands at low areal mass and integrate structurally with composite shells, which is attractive for load-bearing panels [9]. Under high SPLs typical of ascent, multilayer stacks exhibit beneficial nonlinear resistance growth in sub-slits, leading to larger in-situ absorption than linear models would predict; this effect can be exploited but requires care when back-extrapolating chamber data to flight levels [10]. Partial blanket fill remains a high-leverage parameter, with modeling and test evidence indicating that spatially selective placement can outperform uniform fill by avoiding modal coloration and preserving diffusion pathways that equalize field statistics at payload locations [8]. Composite manufacturing constraints identified for glass-fabric RTM fairings (curvature limits, damping windows, and tolerance envelopes) bound the feasible acoustic package configurations and should parameterize the interior models from the outset [5]. Transfer-matrix analyses for curved shells help decouple air-borne from structure-borne spillover and identify curvature–layup pairs with favorable transmission minima before higher-fidelity FE–BEM spot checks [7].

Before presenting the comparative tables, it is helpful to state the integration principle that threads the studies together: exterior fidelity dominates the uncertainty budget at liftoff, while interior economy dictates feasibility over the full bandwidth; the two must be closed by a repeatable handoff of spectra and spatial coherence, then stress-tested with treatment permutations constrained by composite manufacturability (see Table 1).

**Table 1: Numerical workflows for launcher vibroacoustics mapped to mission phases, bandwidths, and coupling choices [1–7]**

| Numerical element / workflow | Target regime and frequency span | Coupling to interior model | Strengths reported | Limitations/assumptions noted |
|---|---|---|---|---|
| URANS of jet/deflector with launch-pad geometry | Liftoff; sub-kHz to multi-kHz with broadband plateaus | Pressure statistics passed to FE–SEA/FE–BEM | Captures impingement physics, corrects deflector-shape sensitivity; improves match to measured envelopes | Costly meshes; pad-specific BCs; limited direct transonic relevance |
| Wall-pressure modeling for ascent beyond pad influence | Early ascent/transonic; higher Strouhal content | Statistical fields mapped to structure/cavity | Economical extension beyond liftoff; enables continuous spectra for interior solvers | Model-form uncertainty where shocks and buffet dominate |
| FE–SEA hybrid interior solver | Full interior bandwidth under design-cycle budgets | Receives exterior spectra/coherence; exports SPL/energy densities | Stable energy partition; parametric liners/blankets; scalable meshes | Reduced spatial detail vs full FE; requires subsystem tuning |
| FE–BEM fully coupled spot checks | Bands with structural-acoustic modal crowding | Direct fluid-structure coupling | High-fidelity validation of finalists | Computationally intensive; limited for sweeps |
| Transfer-matrix for multilayer curved shells | Air-borne path; transmission-loss prediction | Guides layup and package design upstream of FE | Fast parametric sweeps, clear physical knobs | Requires calibration; simplified boundary effects |

The table highlights a disciplined division of labor between exterior URANS at liftoff, statistical extensions into transonic, and interior FE–SEA as the workhorse for design sweeps, with FE–BEM reserved for narrow-band confirmations and transfer-matrix models used to pre-shape composite layups and packages. The principal design implication is that budget should migrate toward exterior fidelity during pad-dominated phases, while interior economy should be protected by using FE–SEA and transfer-matrix accelerators for most iterations, only invoking FE–BEM when modal crowding or unexpected sensitivity appears.

A second comparative view concerns acoustic packages compatible with composite fairings. The next table collates physical mechanisms, mass implications, frequency targeting, manufacturing sensitivity, and evidence types across treatments reported in the reviewed studies (see Table 2).

**Table 2: Acoustic package options for composite payload fairings: mechanisms, mass budgets, targeting, manufacturability, and evidence base [5–10]**

| Treatment / design choice | Physical mechanism | Mass impact | Frequency targeting | Manufacturing sensitivity | Evidence base reported |
|---|---|---|---|---|---|
| Locally resonant liner tuned to liftoff bands | Subwavelength resonance with impedance tailoring | Low to moderate | One-third-octaves near avionics peaks | Geometric and tuning tolerances | Numerical + prototyping with SPL depressions at sensor locations |
| Partial blanket fill with tuned flow resistivity | Broadband porous absorption; spatial field equalization | Low to moderate (by fill %) | Broad, with placement-dependent gains | Placement patterns; resistivity dispersion | NASA modeling and trade study for SPL reduction at payload points |
| Micro-perforated sandwich with hierarchical honeycomb core | Viscous losses in sub-slits + resonant synergy with core | Low at given stiffness | Broad; extended to lower bands by hierarchy | Hole tolerances; core fabrication | Chamber and modeling evidence for broadband absorption at low areal mass |
| Nonlinear multilayer dissipative stack | SPL-dependent resistance growth in slits under high intensity | Moderate | Low-frequency enhancement at high SPL | Layer spacing, slit geometry | High-intensity chamber evidence; nonlinear absorption gains |
| Curved-shell layup and package sweep via transfer-matrix | Impedance matching and TL shaping along air-borne path | Zero (design selection step) | Tunable by laminate/curvature choices | Requires calibration to boundary conditions | Analytical-numerical agreement with FE–BEM baselines |
| Composite RTM fairing construction constraints | Damping window, curvature, tolerance envelopes | Governs feasible package mass | Indirect: sets radiation efficiency and TL minima | RTM process limits and quality control | Structural/aero studies informing acoustic parametrization |

The comparisons suggest a pragmatic stacking order for design: begin with layup/curvature choices shaped by transmission-loss predictions from transfer-matrix analysis [7], overlay a low-mass resonant liner tuned to liftoff plateaus [6], distribute partial blankets to suppress spatial hot spots without modal over-coloration [8], and consider micro-perforated hierarchical sandwiches where load-bearing panels must contribute acoustic work at minimal areal mass [9]. Nonlinear stacks promise additional margin at flight-representative SPLs, but their parameter dispersion argues for conservative tuning and robust test correlation before adoption in qualification campaigns [10]. Composite manufacturing findings constrain the attainable design region, so structural and acoustic teams should share laminate and tolerance parametrizations early to avoid infeasible optima [5].

Several cross-cutting uncertainties remain visible through the lens of these studies. First, the fidelity of exterior liftoff fields still dominates prediction uncertainty; differences in deflector geometry and pad boundary conditions propagate strongly into interior spectra, which favors investment in URANS quality and site-specific model calibration [2–4]. Second, interior FE–SEA accuracy hinges on subsystem parameter identification, especially for liners and blankets, which suggests structured test campaigns to identify effective impedances and flow resistivities across manufacturing spreads before locking design targets [1; 6; 8]. Third, transmission-loss predictions for curved composite shells remain sensitive to boundary conditions and curvature-induced mode conversion; transfer-matrix models offer speed and insight but should be anchored to FE–BEM spot checks in bands where cavity–structure coupling is strongest [7]. Fourth, claims of improved absorption under high SPL demand careful extrapolation from chamber proxies to fairing volumes, due to scale and field-diffuseness differences; nonlinear benefits should be treated as upside until in-situ correlation is obtained [10].

Finally, multi-objective trade-offs (mass, manufacturability, thermal constraints, contamination control) must be kept explicit when selecting packages such as micro-perforated hierarchical sandwiches; the attractive broadband gains at low areal mass intersect with hole-tolerance and core-fabrication realities that affect yield and quality assurance.

## 5. Conclusion

Vibroacoustic reliability of composite payload fairings depends on high-fidelity exterior prediction and computationally scalable interior modeling. URANS simulations anchored to pad-specific deflector configurations should provide the primary source field for liftoff. FE–SEA hybrids supply the backbone for interior broadband analysis, while transfer-matrix solvers accelerate laminate and treatment evaluation prior to FE–BEM spot checks.

Composite-compatible acoustic packages, including locally resonant liners, partial blanket fills, micro-perforated hierarchical sandwiches, and nonlinear multilayer dissipative stacks, can be combined to meet qualification limits at minimal added mass when tuned appropriately and cross-validated with test data.

These methods collectively support the design of next-generation composite fairings and contribute to broader aerospace and national objectives by improving prediction accuracy, reducing qualification risk, and advancing the reliability of critical launch-vehicle structures.

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