ACOUSTIC SYSTEMS

ACTIVE ACOUSTIC SYSTEMS

An Architectural and Acoustic Perspective

Technical White Paper

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Executive Summary

Active Acoustic Systems are often treated as functionally interchangeable. In reality, they are not architecturally equivalent in their underlying electroacoustical working principles.

This distinction is not merely semantic, but fundamentally determines how systems behave, scale, and integrate within architectural space. As a consequence, not all system architectures can be meaningfully applied in every room condition. Depending on the underlying acoustic properties of the space, certain approaches may reach practical limits in achievable decay extension, spectral balance, or perceptual coherence.

Although the term “active acoustics” is widely used to describe electronic enhancement of room acoustics, systems operating under this label differ fundamentally in how they interact with the physical acoustic environment. These architectural differences determine stability behaviour, achievable decay extension, spectral neutrality, perceptual coherence, and operational robustness.

Importantly, architectural principle interacts directly with room conditions. No single system architecture can guarantee identical acoustic outcomes in every spatial context. The physical characteristics of the room - including volume, absorption, modal behaviour and existing energy distribution - remain decisive in defining what can be achieved and how coherently it can be realised.

Active Acoustic Systems extend the functional range of architectural volumes by introducing controlled electro-acoustic interaction with the room. Unlike passive acoustic design - which shapes reverberation time and energy distribution through geometry, volume and material properties - active systems influence the behaviour of acoustic energy after construction. While variable passive measures such as movable absorptive elements or adjustable reflectors provide limited adaptability, they remain constrained by physical boundaries and mechanical feasibility. Active systems operate within the same physical laws, but introduce an additional dynamic control layer.

From an architectural perspective, three fundamental system principles can be identified:

- Regenerative systems, based on closed-loop microphone-loudspeaker interaction that extends the physical decay behaviour of the room through controlled energy recirculation, inherently increasing the overall sound energy in the space.
- In-line systems, based on open-loop signal-domain processing that generates a parallel algorithmic reverberant field superimposed onto or integrated with the natural room response.
- Hybrid systems, integrating regenerative and in-line domains within a unified architecture.

These approaches differ not merely in implementation, but in their relationship to the room itself. In closed-loop architectures, the room becomes an integral system component. In open-loop architectures, the room remains the reference environment against which electronic contribution must align.

While architectural principle defines fundamental behaviour, practical performance depends strongly on system design, implementation, and calibration. Not all realisations of a given approach are equivalent in acoustic outcome.

Meaningful evaluation of Active Acoustic Systems therefore requires an architectural and acoustic framework. Reverberation time alone is insufficient. Quality is determined by time-domain coherence, energy proportionality, clarity preservation, spatial integration, stability margins, and robustness under changing conditions.

This document establishes such a framework. It approaches Active Acoustic Systems not as signal-processing tools, but as architectural acoustic interventions governed by the same physical and perceptual principles that define room acoustics itself.

Its objective is to clarify how Active Acoustic Systems operate, how different architectural principles interact with the physical acoustic environment, and how their behaviour should be evaluated from an architectural and acoustic perspective.

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Terminology and Scope

Electronically assisted room acoustics has been described under a range of terms in professional practice and technical literature. Common expressions include *Active Acoustics*, Assisted Acoustics System, *Electronic Acoustic Enhancement*, *Electronic Acoustic System, Acoustic Enhancement Systems*, and *Electronic Reverberation Systems*. The designation *Variable Room Acoustic Systems (VRAS)* is also encountered in some contexts.

The broader term *Variable Acoustics* is widely used to describe strategies that enable adaptation of room acoustic behaviour. Importantly, this term may refer either to passive architectural measures - such as movable absorptive or reflective elements - or to electro-acoustic systems employing microphones, signal processing and loudspeakers. The expression *Active Variable Acoustics* is sometimes used to distinguish electronically controlled systems from purely mechanical variability.

The term *Virtual Acoustic System (VAS)* appears in related discussions. VAS typically refers to systems based on closed-microphone techniques and convolution with impulse responses of existing spaces, or with responses generated through acoustic modelling, aiming to recreate external acoustic environments. Such approaches focus on acoustic reproduction rather than on interaction with and extension of the host room’s inherent energy behaviour, and therefore fall outside the scope of this document.

In contemporary professional discourse, ***Active Acoustics*** has emerged as the most widely adopted umbrella term for electro-acoustic systems that extend or modify the acoustic behaviour of architectural spaces.

Key Definitions

Regenerative System
Active acoustic architecture based on controlled electro-acoustic feedback in which acoustic energy is recirculated through the room.

In-line System
Architecture in which reverberant energy is generated within the signal domain and reproduced into the room without aiming at acoustic recirculation.

Hybrid System
Architecture combining regenerative and signal-derived domains within a unified system.

Time-Domain Coherence
Continuity and proportionality of acoustic energy decay across early and late temporal regions.

Energy Proportionality
Balanced distribution of acoustic energy across temporal and spectral domains during reverberation extension.

Spatial Integration
Perceptual merging of electronically reproduced energy with the natural acoustic response of the room.

Stability Margin
Distance between operational loop gain and the onset of instability or perceptual artefacts.

1. Introduction – Active Acoustic Intervention in Architectural Context

The acoustic behaviour of a room is fundamentally determined by its geometry, volume and material composition. Through reflection, absorption and diffusion, architectural design establishes baseline values for reverberation time, clarity, strength and spatial impression. Once constructed, these characteristics are largely fixed.

Variable passive acoustic measures - including retractable absorptive banners, adjustable reflectors, rotating diffusive panels or deployable curtains - can extend this baseline within defined limits. Increasing or decreasing absorption alters decay time; modifying reflective surfaces influences early energy distribution. In exceptional cases, structural modification may alter effective volume. However, these strategies remain physically constrained and cannot provide continuous, program-dependent control across a broad operational range.

Active Acoustic Systems introduce a different form of intervention. Rather than altering physical boundaries, they influence how acoustic energy develops and circulates within the existing architectural volume. Through microphones, signal conditioning and/or processing, and distributed loudspeaker systems, energy present in the room can be captured, controlled and reintroduced in real time.

Importantly, electronic intervention does not suspend the physical laws governing room acoustics. Early reflections, diffuse-field development, modal behaviour and frequency-dependent decay remain decisive. Active systems operate within these constraints. When properly designed, they do not add an audible electronic layer, but modify how the room behaves acoustically as a whole.

In practice, Active Acoustic Systems are applied to venues that must support multiple acoustic functions within a single architectural volume. Concert halls, theatres, houses of worship and multi-purpose cultural spaces (i.e. culture houses, rehearsal spaces) often require acoustic conditions that vary substantially between speech, amplified performance and unamplified (classical) music, such as chamber music, opera, classical ballet, symphonic music, choir, organ repertoire as well as brass band, for example. Constructing separate rooms for each function is rarely feasible. Active systems therefore extend the functional flexibility of architectural design.

Despite this shared objective, systems described as “active acoustics” vary widely in architecture and behaviour. Some approaches physically extend room decay through controlled feedback interaction; others generate algorithmic reverberant fields within the signal domain and reproduce them into the space. These architectural distinctions determine stability behaviour, perceptual integration and achievable acoustic coherence.

Understanding Active Acoustic Systems therefore requires more than a description of components or processing features. It requires an architectural perspective that examines how acoustic energy is captured, conditioned and reintroduced into the room, and how this interaction manifests in measurable and perceptual behaviour.

2. Architectural System Principles

Active Acoustic Systems can be categorised into three principal architectural approaches. These principles are defined not by brand, implementation detail or feature set, but by their fundamental relationship to the acoustic environment.

2.1 Regenerative Systems

Regenerative Active Acoustic Systems are based on controlled acoustic feedback between microphones and loudspeakers. Acoustic energy present in the room is captured, controlled, and reintroduced into the same space in a manner that promotes spatial redistribution and diffuse-field development.

The extended decay is an emergent property of the regenerative loop. Each electro-acoustic cycle introduces delay, filtering, and spatial decorrelation, producing a controlled exponential decay that remains physically coupled to the room's inherent acoustic behaviour.

Rather than generating an independent reverberation field, the system "amplifies" the sound field in order to extend the natural reverberation process of the space itself.

Because regenerative systems operate as closed-loop interactions, their behaviour is inseparable from the acoustic properties of the room. Geometry, absorption distribution, modal structure, and occupancy directly influence achievable loop gain, spectral balance, and stability margin. The room becomes an integral component of the system rather than a passive container.

A defining characteristic of regenerative architectures is that most captured energy is subject to recirculation. This includes desired signal energy, background noise, and residual system noise. As decay is extended, the effective noise floor rises proportionally. Practical performance is therefore constrained by gain-before-instability limits and perceptual noise tolerance.

When properly balanced, regenerative systems can achieve a high degree of perceptual integration. Because the same energy processes govern both early and late decay, the extended reverberation may be perceived as an intrinsic attribute of the space rather than an external addition. However, closed-loop behaviour also introduces sensitivity to environmental change and requires disciplined management of channel interaction and loop structure.

2.2 In-line Systems

In-line Active Acoustic Systems operate primarily within the signal domain. Microphone signals or direct inputs are electronically processed to derive reverberation or spatial impression, which is then reproduced into the room via distributed loudspeakers.

Unlike regenerative systems, in-line architectures do not fundamentally modify the physical decay behaviour of the space itself. Instead, reverberant energy is generated within the signal domain and reproduced into the room as an additional acoustic field that coexists with the room's natural response.

Although microphones may capture the part of the existing sound field of the space, this is not the goal, the reverberant behaviour of the room itself is not extended through electro-acoustic recirculation. The processor determines the temporal and spectral structure of the generated reverberant field, which is reproduced through the loudspeaker system.

In practice, in-line systems may differ in how the acoustic field is sampled. Some architectures derive their processing primarily from source microphones located on stage or close to the sound source.

Others incorporate additional room microphones that capture the existing acoustic field of the space. While such approaches reference the room's sound field during processing, the system remains open-loop: the generated reverberant energy is not produced through recirculation of acoustic energy within the room itself, which can therefore be minimised.

Because in-line systems do not form a closed acoustic loop with the room, their stability behaviour is not constrained by regenerative feedback interaction. Spectral shaping, temporal structure and spatial distribution can therefore be controlled with high predictability, and background noise is not subject to recirculation.

From an architectural perspective, in-line systems provide controlled additive modification. Their influence remains signal-derived rather than physically coupled, but when carefully designed the perceptual result can still integrate convincingly with the room's existing acoustic character.

2.3 Hybrid Systems

Hybrid Active Acoustic Systems combine regenerative and in-line domains within a unified architectural framework. A regenerative domain may extend physically coupled diffuse-field energy, while an in-line domain provides signal-derived refinement of decay shaping, spectral balance, or spatial distribution.

The principal challenge of hybrid systems lies not merely in combining both domains, but in managing their interaction. Regenerative and in-line contributions must align coherently in time, frequency, spatial distribution, and decay behaviour to form a unified acoustic response. Misalignment can introduce perceptual artefacts such as double decay slopes, spectral discontinuities, spatial incoherence, or a perceived separation between early and late energy.

A critical factor in successful hybrid integration is the treatment of decorrelation and energy density across domains. If the signal-derived field develops statistical properties that conflict with the regenerative field, the acoustic result may appear layered rather than unified. Conversely, when decorrelation strategy, spectral shaping, and temporal structure are architecturally coordinated, the transition between regenerative and in-line domains can become perceptually seamless.

Hybrid architectures offer adaptive flexibility in relation to room characteristics. In highly absorptive environments, regenerative interaction may establish sufficient diffuse-field energy to support natural decay extension. In more reflective spaces, in-line shaping can refine temporal or spectral behaviour without excessive recirculation.

However, the coexistence of closed-loop and signal-derived domains increases architectural complexity. Stability management, gain structuring, decorrelation strategy, temporal alignment, and spatial calibration must be treated as a single integrated system problem rather than as independent layers.

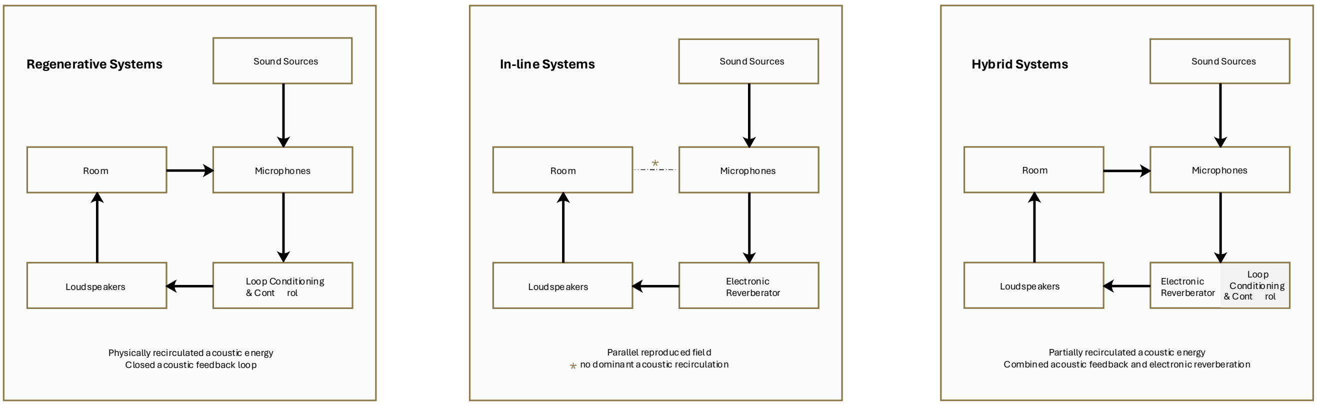

Figure 1. *Physical interaction models in regenerative, in-line and hybrid active acoustic architectures – simplified infographic.*

3. Physical Room Interaction as Defining Criterion

The essential distinction between architectural principles lies in their degree of physical room interaction.

In closed-loop regenerative systems, acoustic energy is recirculated within the physical environment. The overall decay behaviour and diffuse-field energy density are influenced through controlled reinforcement. The room participates actively in system behaviour, and architectural properties - geometry, absorption distribution, and modal structure - directly shape performance.

In open-loop in-line systems, the room remains the reference acoustic environment. Reverberant energy is derived within the signal domain and reproduced into the space, but the physical energy decay behaviour of the room itself remains unchanged. The electronically generated field must therefore achieve perceptual alignment with the natural response rather than modify it physically.

Physical interaction introduces inherent constraints. Stability margin, spectral neutrality, and usable loop gain are influenced by inter-channel coherence and feedback interaction. Without controlled management of channel relationships, reinforcement may become spectrally or spatially concentrated, reducing stability margin and introducing perceptible coloration.

For this reason, robust Active Acoustic Systems incorporate strategies that reduce unwanted coherence between channels while preserving overall energy contribution. By limiting excessive spectral and temporal alignment across feedback paths, the system increases usable gain-before-instability and supports more uniform diffuse-field development. The objective is not to create audible modulation, but to maintain acoustic transparency and stability within the physical environment.

Recognising physical room interaction as the defining criterion shifts evaluation from feature comparison to behavioural analysis. Two systems may both offer adjustable reverberation time, yet differ fundamentally in how energy circulates within the space, how stability is maintained, and how perceptual coherence is achieved.

An architectural perspective therefore provides the foundation for interpreting subsequent acoustic behaviour. Time-domain structure, energy distribution, and perceptual integration are all consequences of how the system interacts with the room.

4. Time-Domain Structure and Coherence

Time-domain behaviour is one of the most decisive indicators of architectural robustness in Active Acoustic Systems. While reverberation time is frequently used as a headline metric, it does not describe how decay develops, how early and late energy relate, or how continuity is perceived during real programme material.

In natural rooms, early decay time (EDT) and later decay metrics such as T20 or T30 arise from the same physical processes. Early reflections, diffuse-field build-up and energy dissipation are governed by the geometry and absorption of the space, producing a continuous decay profile whilst increasing the reflection density with time. The auditory system interprets this continuity as spatial plausibility.

In Active Acoustic Systems, such coherence cannot be assumed. Architectural constraints - including stability limits, channel interaction, spectral shaping and spatial redistribution - may affect early and late energy differently. When late decay is extended without proportional influence on early decay behaviour, perceptual discontinuity arises.

4.1 EDT, Running Reverberation and Decay Plausibility

Early Decay Time (EDT) represents the initial rate of energy decay and plays a dominant role in spatial perception during ongoing sound. It is this early decay - often experienced as “running reverberation” - that informs the auditory system about the apparent size, distance and acoustic character of a space.

While T_{30} describes the later decay slope of the impulse response - often experienced as “terminal reverberation”, listeners do not primarily infer room character from the late reverberation tail. Instead, spatial impression is largely shaped during the first portion of decay, when direct sound and early reflected energy interact perceptually.

If T_{30} is extended while EDT remains comparatively short or energetically weak, the perceived space does not expand proportionally. The listener continues to perceive a room corresponding to the shorter early decay, while the extended late tail may be interpreted as an added effect rather than as an intrinsic spatial property. In such cases, reverberation becomes episodic rather than structurally integrated.

In physically interactive systems, regenerative energy contributes from the onset of decay, allowing early and late decay characteristics to evolve in a more proportionate manner. In signal-derived architectures, careful alignment between generated reverberant energy and the room’s natural early response is required to preserve continuity between running reverberation and late decay.

The objective is not numerical equivalence between EDT and T_{30}, but perceptual plausibility. A coherent relationship between direct sound, early decay energy and late reverberation is essential for maintaining spatial credibility across operating conditions.

4.2 Decay Form versus Decay Value

Acoustic quality is not defined by decay duration alone, but by decay form and its content.

The integrated decay curve, derived through Schroeder integration, reveals whether energy decay follows a continuous exponential trend or exhibits changes in slope. Deviations from a consistent decay gradient may indicate the coexistence of distinct energy contributions that are not temporally unified.

Energy-Time Curves (ETC) provide complementary insight into early reflection structure and the onset behaviour of late energy. While visual smoothness of the ETC is not an objective in itself, the temporal plausibility of reflection density, spacing, and late-field emergence is perceptually significant.

In coherent systems, early reflections transition progressively into diffuse energy build-up, producing a decay trajectory that appears structurally continuous. In less integrated architectures, additional reverberant energy may manifest as a secondary decay regime - often perceived as a “double slope” or layered decay rather than as a unified acoustic response.

4.3 Artefact Recognition in Active Systems

Architectural constraints may manifest as identifiable artefacts in time-domain behaviour:

- Detached late decay regimes
- Discontinuities between early and late decay slopes
- Excessive delay of early energy due to signal-path latency
- Temporal smearing resulting from misaligned or incoherently injected energy

These artefacts are not merely measurement anomalies. They correspond directly to perceptual consequences, including artificial spaciousness, reduced articulation, loss of clarity, or the impression that reverberation is electronically appended rather than spatially inherent.

Recognition of such behaviour requires interpreting time-domain data in the context of system architecture. Measurements must be evaluated not in isolation, but in relation to energy circulation principles, coupling strategy, and temporal alignment within the active system.

4.4 Decorrelation and Stability in Time-Domain Behaviour

In closed-loop and multi-channel regenerative systems, inter-channel coherence directly influences time-domain behaviour. When multiple feedback paths reinforce similar spectral components in a temporally aligned manner, loop gain may concentrate around dominant frequencies or spatial modes, reducing stability margin and disturbing decay uniformity.

Controlled decorrelation reduces excessive alignment between channels. By limiting spectral and temporal coherence across feedback paths, the system increases usable gain-before-instability and promotes more uniform spatial and spectral energy distribution within the diffuse field.

Different architectural strategies exist to achieve this reduction in coherence. In time-constant systems, decorrelation is achieved through stationary structural means - such as fixed spectral shaping, phase distribution, or spatial diversity - resulting in stable, non-modulating decay behaviour. The time-domain response remains statistically stationary, and no intentional parameter variation is introduced over time.

In time-variant systems, coherence may be reduced through controlled modulation of delay, phase, or related parameters. By dynamically varying relationships between feedback paths, the system mitigates persistent reinforcement patterns and increases stability margin. Such approaches function as a form of dynamic decorrelation.

While time-variant strategies can effectively prevent stationary tonal build-up, perceptual transparency depends on the rate and depth of modulation. In harmonically sensitive material, excessive time variance may introduce subtle pitch instability, moving spectral coloration, or a sense of temporal fluctuation.

This may confuse people with absolute pitch hearing. The perceptual outcome therefore reflects a balance between dynamic coherence management and acoustic stationarity.

Effective decorrelation - whether time-constant or time-variant - is not intended to introduce audible movement or artificial modulation. Its purpose remains architectural: to prevent localised reinforcement, reduce tonal dominance, and maintain a perceptually continuous and physically credible decay structure.

In this sense, decorrelation is not an enhancement feature, but a structural prerequisite for stable and proportionate decay extension.

5. Energy Distribution and Proportionality

Reverberation extension inevitably affects overall energy density within the room. Acoustic strength (G) provides a reference for total sound energy relative to a free-field condition and is closely associated with perceived loudness, presence, and acoustic support.

In Active Acoustic Systems, extending decay without proportional control of energy distribution may alter the spatial character of the environment in unintended ways.

5.1 Strength and Perceived Density

Increasing late energy generally raises overall strength. While moderate increases may enhance envelopment and warmth, excessive accumulation can produce a perceptually dense, hard, or fatiguing acoustic environment.

Importantly, perceived spatial enlargement does not scale linearly with energy increase. A room may become louder without sounding larger. This occurs when added energy lacks proportional early support, when decay form becomes segmented, or when spectral balance shifts disproportionately.

In regenerative systems, increases in strength are inherently coupled to recirculated acoustic energy, including background noise and residual system noise. In signal-derived architectures, strength may be adjusted more independently of the room’s physical decay, yet perceptual integration depends on how the introduced energy aligns temporally and spectrally with the natural response.

5.2 Early-Late Proportionality

Clarity and spaciousness depend on the ratio between early and late energy. Excessive late emphasis reduces articulation and temporal definition; excessive early emphasis reduces spatial depth and envelopment.

Architectural quality lies not in maximising any single parameter, but in preserving proportional relationships. Extending reverberation time while maintaining articulation requires that early support and late decay remain perceptually and energetically coherent.

This interdependency illustrates why Active Acoustics cannot be reduced to a single adjustable metric such as reverberation time. Spatial impression emerges from proportional balance across temporal regions.

In spaces where architectural conditions provide limited early reflection support, Active Acoustics may complement the natural energy distribution by effectively filling in missing early reflections, thereby restoring a more balanced development between early and late acoustic energy.

5.3 Spectral Proportionality

Perceived coherence also depends on frequency-dependent behaviour.

Mid-frequency bands play a dominant role in spatial perception and speech clarity. Low-frequency enhancement contributes to warmth and power, but introduces modal sensitivity, increased energy storage, and potential masking effects.

Spectral proportionality requires that decay extension remains balanced across frequency bands. Frequency-dependent divergence - whether arising from room modes, loop gain concentration, uneven spectral shaping, or non-uniform loudspeaker injection - compromises naturalness and perceptual unity.

Energy distribution must therefore be evaluated both temporally and spectrally. A plausible acoustic environment depends on proportionality across time, frequency, and spatial domains rather than on isolated parameter optimisation.

6. Clarity, Intelligibility and Functional Modes

Clarity parameters such as C_{50} and C_{80} describe the ratio between early and late energy within defined temporal windows. In Active Acoustic Systems, these metrics function primarily as behavioural indicators of energy proportionality rather than as independent optimisation targets.

6.1 Clarity as an Integration Indicator

In natural rooms, clarity values emerge as a consequence of geometry, absorption distribution, and source–receiver relationships. In active systems, changes in clarity reflect how successfully early and late energy remain proportionally linked during decay extension.

A moderate reduction in C_{50} or C_{80} may be acceptable in music-oriented modes if increased late energy is accompanied by coherent spatial development. However, excessive decline signals reduced articulation, temporal masking, and perceptual blur.

Notably, clarity degradation often becomes most apparent at intermediate extension settings rather than at maximum values. At these mid-range conditions, proportional relationships between early support and late decay may be less structurally balanced.

Clarity therefore serves as an integration indicator: it reveals whether decay extension preserves functional coherence or introduces temporal imbalance.

6.2 Speech, Music and Multi-Mode Operation

Different programme material emphasises different acoustic priorities.

Speech-oriented modes require stable source localisation, strong early support, controlled late energy, and preservation of intelligibility cues. Music-oriented modes may accommodate increased late energy, provided articulation, blend, and tonal definition remain intact.

In multi-purpose environments, transitions between these operating conditions must occur without perceptual discontinuity. The ability to move between functional modes while maintaining temporal, spectral, and spatial coherence reflects architectural robustness rather than feature abundance.

Mode switching is therefore not merely a parameter change, but a test of proportional stability across operating states.

6.3 Intermediate-State Quality

Systems that appear convincing at extreme settings may reveal structural imbalance at intermediate states. Because practical operation frequently occurs between minimum and maximum extension, evaluation must account for transitional behaviour across the full operating range.

Quality in Active Acoustics emerges not from peak parameter values, but from stable proportional relationships maintained across modes, extension levels, and programme conditions.

7. Spatial Integration and Localisation Integrity

Spatial integration constitutes a defining quality criterion in Active Acoustic Systems. Even when time-domain behaviour and energy proportionality are well controlled, spatial incoherence may reveal the electronic nature of the intervention and compromise perceived naturalness.

A room is perceived as acoustically authentic when direct sound remains stably anchored to its source while reverberant energy develops as a diffuse, enveloping field that does not attract attention to discrete reproduction points. The objective is therefore not merely to distribute sound, but to establish a spatially integrated energy field that remains perceptually subordinate to the primary source.

7.1 Source Anchoring and Perceptual Hierarchy

In natural rooms, localisation is dominated by early-arriving energy and stable directional cues, while late reverberation contributes primarily to envelopment and apparent room size. An Active Acoustic System must preserve this perceptual hierarchy.

If electronically reproduced energy introduces dominant or competing directional cues - whether through excessive level, insufficient decorrelation, or spatially localised injection - listeners may experience image shift, reduced source stability, or awareness of loudspeaker locations.

Spatial quality in Active Acoustics therefore depends on maintaining:

- Stable localisation of direct sound and controlling apparent source width (ASW)

- Gradual and plausible spatial growth of reverberant energy
- Minimal directional competition between reproduced field and natural cues

7.2 Distributed Injection Versus Discrete Reproduction

Active systems typically rely on distributed loudspeaker networks. The purpose of distribution is not to create a multi-source direct field, but to inject reverberant energy in a manner that supports diffuse-field development.

If loudspeaker density is insufficient, or if injection points remain perceptually discrete, reproduced energy may remain localised to loudspeaker positions. This is particularly critical in mid- and high-frequency ranges, where directional sensitivity is strongest. In such cases, reverberation may be perceived as emanating from identifiable sources rather than as an intrinsic spatial attribute of the room.

Sufficiently distributed injection reduces localisation of the reproduced field and supports perceptual merging between electronic and natural responses.

7.3 Coherence, Colouration and Spatial Artefacts

Spatial artefacts may arise from several architectural conditions:

- Excessive inter-channel coherence leading to localised reinforcement
- Spectrally dominant injection zones creating tonal concentration
- Temporal misalignment between injected energy and natural decay
- Non-uniform spatial energy distribution across the audience area
- Comb filtering resulting from insufficient acoustic or electro-acoustic decorrelation

When reproduced energy from multiple channels arrives with partially coherent phase relationships, frequency-dependent interference patterns may occur. While often subtle, these effects can reduce spectral neutrality and introduce position-dependent coloration, particularly at higher frequencies.

Such artefacts frequently manifest as uneven envelopment, perceptual asymmetry, or listener-dependent variation in quality. A system may appear coherent at one listening position yet artificial at another.

Spatial integration therefore requires evaluation across the listening area rather than at a single measurement point. The system must be understood as a spatially distributed intervention whose perceptual validity depends on uniform behaviour throughout the audience zone.

7.4 Spatial Robustness Under Changing Conditions

Occupancy variation modifies absorption characteristics, particularly in mid- and high-frequency bands. In regenerative architectures, such changes directly affect loop behaviour through altered energy dissipation and redistribution. As audience density increases, achievable gain margins and decay characteristics may shift.

Architecturally robust systems tolerate realistic occupancy variation without perceptible degradation of stability, clarity, or spatial coherence. Proportional relationships must remain intact across expected audience conditions.

Environmental factors such as temperature and humidity influence air absorption and high-frequency decay. Although typically gradual in effect, these variations may subtly alter spectral balance over time. Long-term stability therefore requires calibration strategies that acknowledge environmental variability rather than assuming static room conditions.

Spatial integration is not a static achievement but an operational requirement maintained across programme types, audience presence, and seasonal variation.

8. Microphones, Loudspeakers and Low-Frequency Strategy in Architectural Context

The selection and deployment of microphones and loudspeakers do not define the architectural principle of an Active Acoustic System, but they strongly influence how that principle manifests within a specific room. Microphones and loudspeakers function as interfaces between physical space and electro-acoustic processing, shaping how energy is sampled, redistributed and perceived.

This section remains intentionally principled. Specific configuration strategies are room-dependent and belong to project design and commissioning rather than to a general architectural framework.

8.1 Microphones as Energy-Sampling Interfaces

Microphones determine how the acoustic environment enters the system. Their placement and polar characteristics influence:

- the balance between direct sound capture and diffuse-field sampling,
- sensitivity to localised sources,
- the spectral content entering the processing chain,
- and the degree of coupling to ambient noise.

The polar response of microphones is therefore a decisive architectural factor. Directional characteristics must be evaluated in relation to room geometry, source distribution and intended operating modes. A highly directional microphone may emphasise direct sound and reduce diffuse sampling, while broader patterns may increase spatial averaging but also capture more ambient energy.

In regenerative systems, microphone behaviour directly influences loop stability and spectral neutrality. In signal-derived architectures, it shapes how plausibly early energy is captured and extended.

8.2 Loudspeakers as Spatial Redistribution Interfaces

Loudspeaker systems define how controlled energy is reintroduced into the room. Their density, spatial distribution and dispersion characteristics influence:

- the formation of a diffuse reverberant field,
- spatial uniformity across the audience area,
- perceptual localisation risk,
- and coupling behaviour in regenerative loops.

Loudspeaker directivity must be considered in architectural context. Narrow dispersion may increase the risk of localised reinforcement or image pull, while excessively wide dispersion may reduce control and increase unintended coupling with reflective surfaces. Polar behaviour and coverage characteristics are therefore integral to the spatial strategy of the system rather than secondary electro-acoustic specifications.

In regenerative architectures, loudspeakers are part of the feedback loop and directly influence stability margins and spectral behaviour. In in-line and hybrid systems, they strongly influence how convincingly the generated field merges with the natural room response.

8.3 Frequency Range and Low-Frequency Considerations

Active Acoustic Systems operate across the full audible spectrum, but perceptual changes in clarity, localisation and spatial impression are most strongly associated with mid- and high-frequency behaviour. Extending low-frequency decay introduces additional architectural constraints:

- modal dominance and spatial non-uniformity,
- increased energy storage,
- stronger coupling to stability limits in regenerative systems,
- and potential masking of articulation.

Low-frequency enhancement must therefore be approached with caution. While increased low-frequency support may contribute to warmth and perceived power, disproportionate extension can reduce definition and introduce unevenness across listening positions.

8.4 Low-Frequency Strategy as an Architectural Decision

Low-frequency behaviour is strongly room-dependent. In smaller or highly modal spaces, attempts to extend low-frequency decay may amplify modal irregularities and produce position-dependent coloration. In larger volumes with more diffuse modal distribution, controlled low-frequency extension may enhance warmth and envelopment without compromising clarity.

Low-frequency strategy must therefore be aligned with room volume, modal structure, baseline absorption and functional objectives. It cannot be treated as an independent parameter separate from the architectural context.

8.5 Microphones and Loudspeakers, Decorrelation and Spectral Neutrality

Transducer diversity and spatial distribution also influence the feasibility of effective decorrelation. Limited spatial diversity may increase inter-channel coherence and raise the likelihood of tonal dominance or comb filtering. Conversely, architectural diversity in sampling and injection paths supports reduced coherence, improved stability margins and more uniform spectral behaviour.

Microphones and loudspeakers are thus not merely technical components; they shape the statistical behaviour of energy circulation and the perceptual integrity of the acoustic system. Their characteristics influence not only level and bandwidth, but also the coherence structure that governs stability, spectral neutrality and spatial integration.

9. Architectural Robustness and Multi-Parameter Trade-Offs

Active Acoustic Systems operate within dynamic environments. Audience presence varies, programme material changes, environmental conditions shift, and operating modes are adjusted in real time. Architectural robustness is therefore not demonstrated by extreme parameter values, but by stability, proportional coherence, and predictable behaviour across changing conditions.

9.1 The Multi-Parameter Nature of Active Acoustics

Reverberation time, strength, clarity, spectral balance, spatial distribution, and stability margin are intrinsically interdependent. Adjusting one parameter inevitably influences others.

For example:

- Increasing decay extension may raise overall strength and reduce clarity.
- Increasing loop gain may narrow stability margin and amplify tonal concentration.
- Increasing low-frequency extension may enhance warmth while reducing articulation.
- Increasing spatial density may improve envelopment yet introduce localisation risk.

Active Acoustics must therefore be understood as a balance problem rather than a collection of independent controls. Architectural quality lies in maintaining proportional relationships among variables instead of maximising isolated metrics.

In professional practice, acoustic performance is not defined solely by perceptual judgement, but also by established design criteria. Standards such as ISO 23591 (derived from NS8178) define target ranges for key parameters including reverberation time, sound strength (G), room volume, spatial dimensions and background noise for different types of music use.

These criteria illustrate that acoustic quality is inherently multi-parametric and context-dependent. A robust Active Acoustic System must therefore enable controlled adjustment and verification of these parameters, allowing alignment with project-specific acoustic targets rather than relying on subjective tuning alone.

The practical impact of such criteria has been demonstrated in projects based on NS8178 and ISO 23591, where measurable improvements in rehearsal conditions and acoustic quality have been consistently observed.

9.2 Stability Margin as Architectural Constraint

In regenerative architectures, stability margin defines the practical upper boundary of usable decay extension. Stability is influenced by room absorption, occupancy variation, modal structure, transducer distribution, and inter-channel coherence.

Instability, however, is not a binary event. As loop gain approaches critical limits, perceptual artefacts may emerge before audible feedback occurs. These may include:

- Narrow-band tonal prominence
- Spectral imbalance
- Reduced decay smoothness
- Increased sensitivity to excitation spectrum

Architecturally robust systems avoid operating near such perceptual thresholds. It maintains sufficient margin to preserve neutrality under realistic excitation conditions and occupancy variation.

9.3 Behaviour Across Operating Modes

Multi-purpose venues often require rapid transitions between speech-oriented and music-oriented modes. Such transitions involve coordinated adjustments across multiple parameters rather than simple changes in decay time.

Robust systems preserve:

- Source localisation stability
- Spectral proportionality
- Early–late energy balance
- Spatial coherence

across all operating conditions.

If coherence is achieved only at extreme settings but deteriorates at intermediate values, architectural balance is incomplete. Because practical operation frequently occurs between minimum and maximum extension, evaluation must encompass the full operational range rather than peak performance states.

9.4 Occupancy and Environmental Variability

Audience presence modifies effective absorption, particularly in mid- and high-frequency bands. In regenerative systems, this directly alters loop conditions and achievable decay behaviour. Robust architectures tolerate such variation without requiring constant recalibration or compromising perceptual stability.

Environmental factors such as temperature and humidity influence air absorption and high-frequency decay characteristics. Although gradual in effect, these variables may subtly shift spectral balance over time. Systems designed with appropriate stability margin and calibration discipline remain behaviourally consistent under seasonal variation.

Robustness therefore implies tolerance to realistic variability rather than reliance on static reference conditions.

9.5 Calibration as Acoustic Discipline

Commissioning an Active Acoustic System is not a matter of adjusting isolated parameters to achieve numerical targets. It is an optimisation process that aligns time-domain structure, energy proportionality, spatial integration, and stability margin within the constraints of the room.

Measurement data must be interpreted architecturally. A measured increase in T_{30} is meaningful only if decay form remains continuous. An increase in strength is beneficial only if clarity and spectral balance remain proportionate. Stability margin must be evaluated not only in terms of feedback threshold, but in relation to perceptual neutrality.

Calibration is therefore an acoustic discipline grounded in room behaviour rather than a purely technical configuration exercise.

10. Conclusion - Quality is Architectural and Perceptual

Active Acoustic Systems extend the functional range of architectural spaces by introducing controlled electro-acoustic interaction. They do not replace the physical principles governing room acoustics. Geometry, absorption, modal structure, and environmental conditions remain decisive.

Architectural principle determines how a system interacts with the room. Regenerative, in-line, and hybrid approaches differ fundamentally in their relationship to physical decay behaviour, stability constraints, and perceptual integration. These differences define what can be achieved in a given space and how coherently it can be realised.

Meaningful evaluation of Active Acoustics therefore requires more than specification of adjustable reverberation time. It requires assessment of:

- Time-domain coherence
- Energy proportionality
- Spectral neutrality
- Spatial integration
- Stability margin
- Robustness under changing conditions

Quality emerges when these elements remain proportionate and unified across operating modes and environmental variability.

Robust systems are capable of influencing all relevant acoustic parameters in a coordinated and architecturally coherent manner, within the constraints of the physical environment.

An Active Acoustic System is not judged solely by the extent to which it can extend decay, but by how convincingly it preserves the architectural credibility of the space. When electronic intervention becomes perceptually inseparable from the room itself, the system functions not as an effect, but as a coherent extension of architectural acoustics.

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