Let's augment the terminology by division into two types. The **spectral acoustic crossover** has equal levels at a particular frequency range, the summation of drivers covering different frequency ranges fed by a **frequency (spectral) divider** (section 2.4.4). The **spatial acoustic crossover** has equal levels at a location in the space. It is the summation of sources covering a common frequency range fed by a **spatial divider** (separate speakers and processing channels). A single language is used for the analogous features of both types and the related solutions more easily understood.

The summation zones are common to both types. A primary goal is to place the acoustic crossover in the coupling zone. The secondary goal comes into play when coupling can no longer be maintained: Reach the isolation zone as quickly as possible. Filters accomplish this for spectral crossovers, whereas directional control, splay angle and spacing manage the spatial crossover. In both cases we strive to minimize the combing and transition zones.

4.3.2 Summation zone progressions

Summation zones follow several standard crossover progressions (Fig. 4.22). Let's add A + B and follow them.

- 1-step (coupling (AB)): Speakers with little or no directional control are in extremely close proximity, e.g. subwoofer arrays.
- 2-step (coupling (AB) to cancellation (AB)): coupling on the front side, cancellation in the rear. This is used in cardioid arrays.
- 3-step (isolation (A) to coupling (AB) to isolation (B)): Very achievable in a spectral crossover, but much harder in full-range spatial crossovers. As frequency rises we can expect to see more areas fall into the combing and transition zones, with the realistic goal being minimization, not elimination.
- 5-step (isolation (A) to transition (AB) to coupling (AB) to transition (BA) to isolation (B)): Practically achievable in closely coupled arrays if the coverage angle provides enough isolation to prevent combing.
- 7-step (isolation (A) to transition (AB) to combing (AB) to coupling (AB) to combing (BA) to transition (BA) to isolation (B)): the full progression. This results when isolation is unachievable before combing begins. In the HF this is often the only practical option. Success can be viewed in terms of the share of the progression spent in the combing zone. A progression with more combing zone than coupling and/or isolation zone would rate poorly.

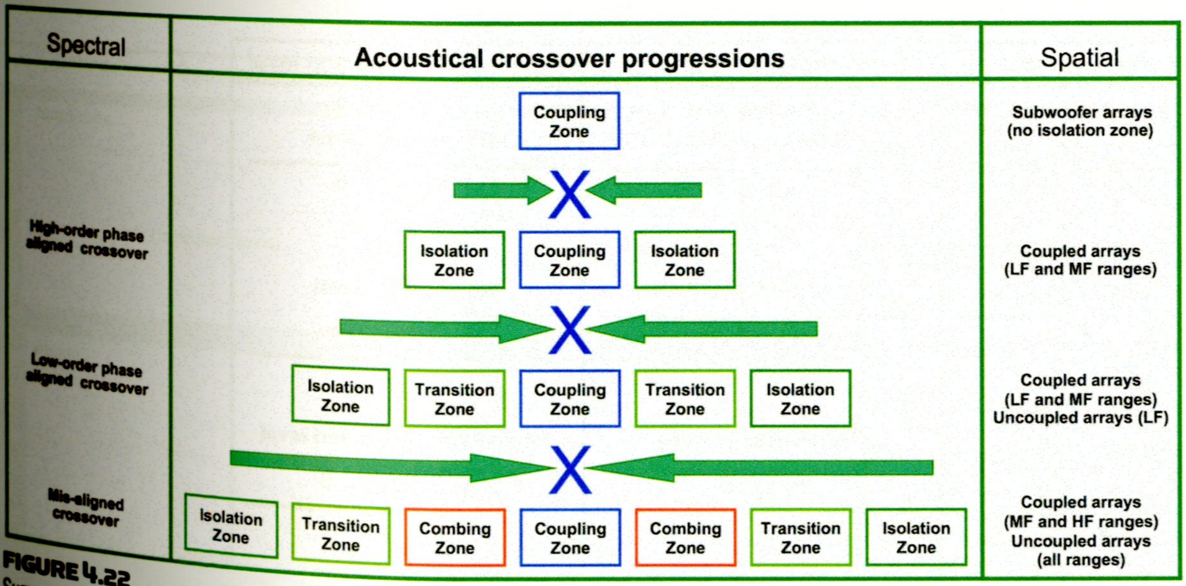


FIGURE 4.22
Summation zone crossover progressions, spectral and spatial

4.3.3 Crossover classifications

4.3.3.1 CLASS

We first classify crossover by the three possible level outcomes to the summation: The crossover range is equal to, greater than or less than the isolated ranges of the individual elements (Fig. 4.23).

Crossover class

- **Unity**: Level through crossover matches the isolated levels (A + B = 0 dB @XAB).
- **Overlapped**: Level through crossover is higher than the isolated levels (A + B > 0 dB @XAB).
- **Gapped**: Level through crossover is lower than the isolated levels (A + B < 0 dB @XAB).

4.3.3.2 SLOPE

Crossover slopes are rated by filter order: first order, second order, etc. The slope steepens as order increases. For spectral crossovers this refers to filters, whereas for spatial crossovers the separation is related to speaker coverage pattern (tighter coverage being higher order).

4.3.3.3 SYMMETRY

We classify crossover symmetry by two possible outcomes: symmetric or asymmetric. Spectral crossovers can have asymmetric filter slopes or filter topologies. Spatial crossovers can be asymmetric by speaker model, splay angles, level and more.

4.3.4 Spectral dividers and spectral crossovers

Let's get practical about the types of spectral crossovers we're likely to find in a modern speaker system. We are either marrying two drivers that already live together in the same box, or arranging one for speakers that are just now meeting.

DRIVER (A AND B) PHYSICAL CONFIGURATION

- Fixed combination: fixed ratio of A and B drivers, known positions, same box.
- Variable combination: variable ratio of A and B drivers, unknown positions, separate boxes.

With fixed combinations we encounter varying levels of manufacturer support.

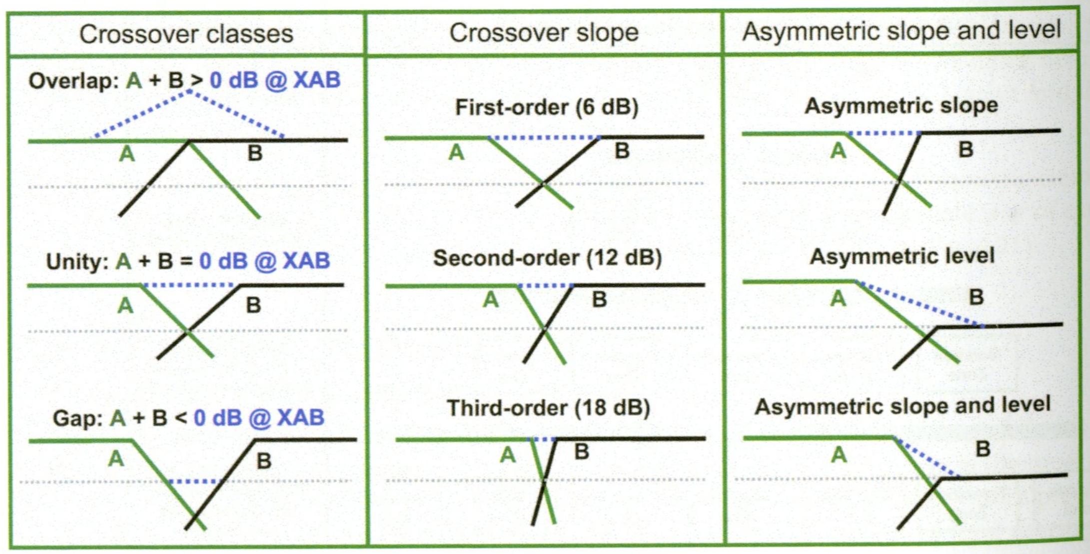
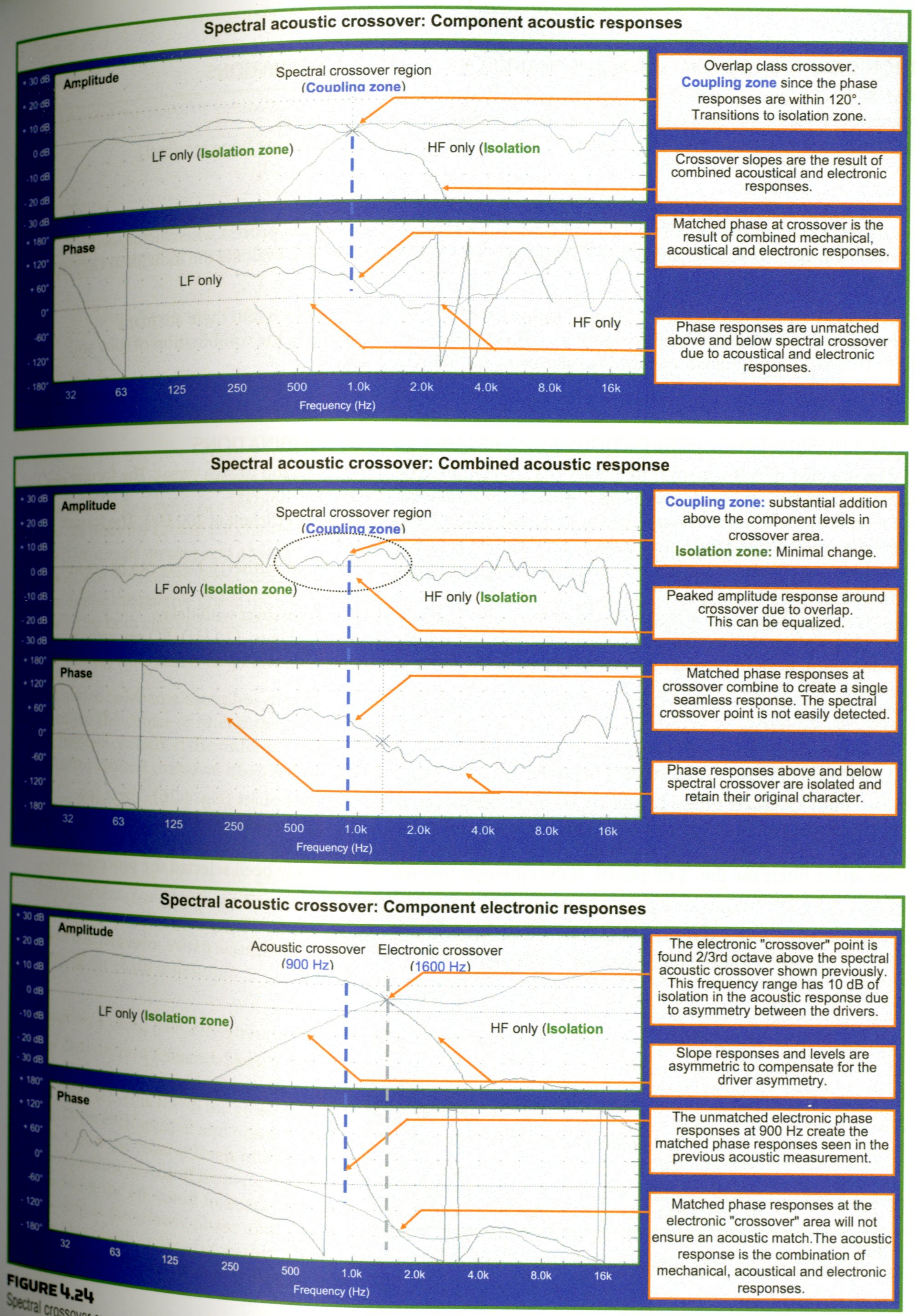


FIGURE 4.23
Spectral crossover classes, slope and asymmetry



Overlap class crossover. Coupling zone since the phase responses are within 120°. Transitions to isolation zone.

Crossover slopes are the result of combined acoustical and electronic responses.

Matched phase at crossover is the result of combined mechanical, acoustical and electronic responses.

Phase responses are unmatched above and below spectral crossover due to acoustical and electronic responses.

Coupling zone: substantial addition above the component levels in crossover area. Isolation zone: Minimal change.

Peaked amplitude response around crossover due to overlap. This can be equalized.

Matched phase responses at crossover combine to create a single seamless response. The spectral crossover point is not easily detected.

Phase responses above and below spectral crossover are isolated and retain their original character.

The electronic "crossover" point is found 2/3rd octave above the spectral acoustic crossover shown previously. This frequency range has 10 dB of isolation in the acoustic response due to asymmetry between the drivers.

Slope responses and levels are asymmetric to compensate for the driver asymmetry.

The unmatched electronic phase responses at 900 Hz create the matched phase responses seen in the previous acoustic measurement.

Matched phase responses at the electronic "crossover" area will not ensure an acoustic match.The acoustic response is the combination of mechanical, acoustical and electronic responses.

FIGURE 4.24
Spectral crossover example showing individual and combined acoustical and electrical responses

ELECTRONIC CONFIGURATION OF A AND B CHANNELS FOR FIXED COMBINATIONS

- Fixed: Settings are not user settable.
- Programmed: Factory presets are loaded into the crossover (hopefully correctly).
- Suggested: Factory settings are programmed by user into the processor (6 dB more hope required).
- Figure it out yourself: cowboy time!

Spectral crossover analysis of fixed driver combinations can be simply a verification process when factory-set, programmed or suggested settings are used. When no guidance is given we need to evaluate the individual elements and make choices (Fig. 4.24).

We also encounter several levels of manufacturer support with variable combinations, but there are many unknowns, leaving us with more need to customize. We will use a typical example, the combination of subs and full-range boxes with a manufacturer-suggested setting of 100 Hz (Fig. 4.25).

SPECTRAL CROSSOVER CONSIDERATIONS FOR VARIABLE DRIVER COMBINATIONS

- Relative quantity affects crossover frequency (e.g. might be two subs with one top or vice versa). The former raises the crossover and the latter lowers it. Level can be adjusted to match at 100 Hz.
- Driver efficiency affects crossover frequency (e.g. sub might be less (or more) efficient at 100 Hz). The former lowers the crossover and the latter raises it. Level can be adjusted.
- Driver location affects time offset between drivers (e.g. sub might be closer (or farther)). Delay can be set to phase align the crossover.
- Driver response differences affect phase offset at crossover. Phase align the crossover with delay.
- Driver ranges affect the overlap at crossover. (e.g. sub and full range share 60 Hz to 120 Hz). EQ can reduce the summation peak in the overlap area or LPF and HPF filters can reduce the overlap to create unity gain at crossover.

4.3.4.1 UNITY SPECTRAL CROSSOVER (LF+HF)

The standard unity crossover brings LF and HF sections together at -6 dB, 0° phase offset (Fig. 4.26). There is a variety of filter slope and topology combinations that can achieve this. The most straightforward (and popular) topology is the Linkwitz-Riley (L-R). The straightforward feature is that the cutoff frequency specified is the -6 dB point (most other filters use the -3 dB point). If the crossover frequency has already been selected the process takes six steps.

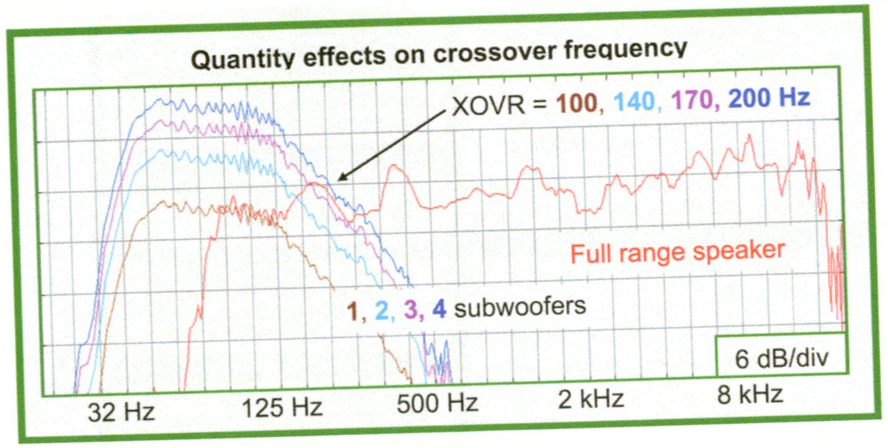


FIGURE 4.25
Quantity effects on crossover frequency (subwoofers vs. mains)

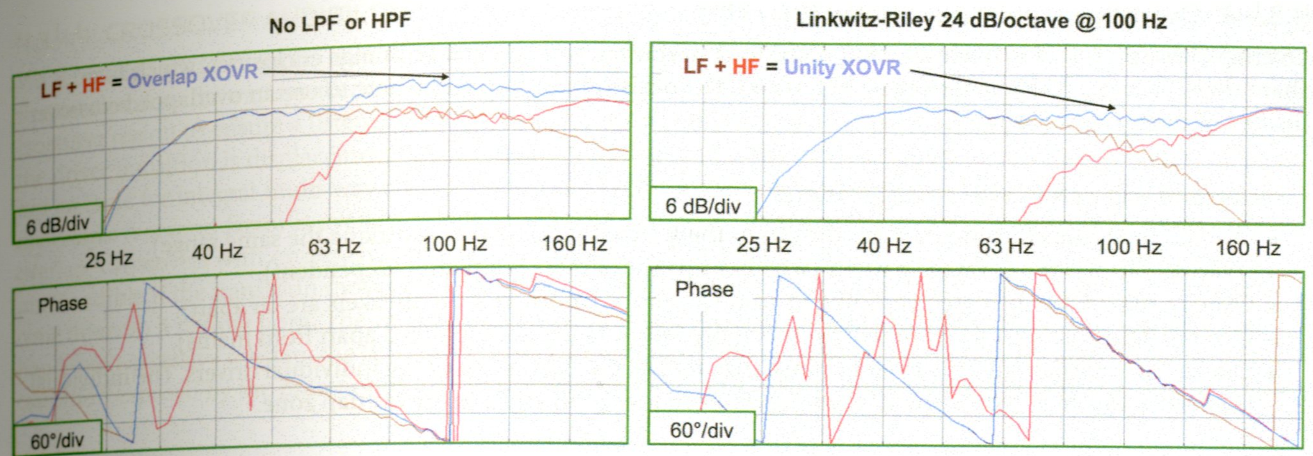


FIGURE 4.26
Overlap and unity spectral crossover examples

Creating a unity gain crossover with L-R filters (LF + HF)

- Determine a reference level: 0 dB.
- Set both the LF and HF channel cutoffs to the target frequency (e.g. 1 kHz).
- Drive each speaker and observe the acoustic response of each individual channel.
- Adjust the relative levels until they match at the crossover target (turn down the louder one).
- Adjust the relative phase until they match at the crossover target (delay the earlier one).
- Drive both channels together. The summed response should match the nominal level and be +6 dB above the individual responses at crossover.

The above holds true regardless of the L-R filter order precisely because the cutoff frequency is the -6 dB point in all cases. The choice of filter order here changes the amplitude response *around* the crossover frequency but not the frequency itself. If the order is changed (or made asymmetric) the phase offset may need adjustment and the behavior around crossover observed to see which gives the smoothest summation.

Other filter topologies (standard LPF, HPF, Bessel, Butterworth, Chebyshev, etc.) require extra work because they use -3 dB as the cutoff specification. An LPF specified at 100 Hz has the same -3 dB point for a first-order slope as an eighth-order one, but a vastly different -6 dB point. To achieve -6 dB at 100 Hz we will need to set the LPF somewhere below 100 Hz, the exact location for which will vary (closer to 100 Hz as filter order rises). The HPF has the same situation in reverse. Electronic settings that would appear to create a gap, such as 80 Hz (LPF) and 125 Hz (HPF), can actually create a unity crossover. As filter order rises, the gap between the electronic settings shrinks but never reaches zero. When asymmetric topologies and/or filter orders are used we must be mindful of where each lands at the -6 dB milestone.

Creating a unity gain crossover with other filter topologies (LF + HF)

- Determine a reference level: 0 dB.
- Set both the LF and HF cutoffs to an octave beyond the target frequency (e.g. 2 kHz for the low and 500 Hz for the HF). This leaves the crossover area free of filter effects for reference.
- Drive each speaker and observe the acoustic response of each individual channel.
- Adjust the relative levels until they match at the crossover target (turn down the louder one).
- Move the LF cutoff frequency down until the response drops 6 dB at the crossover target.
- Move the HF cutoff frequency up until the response drops 6 dB at the crossover target.
- Adjust the relative phase until they match at the crossover target (delay the earlier one).
- Drive both channels together. The summed response should match the nominal level and be +6 dB above the individual responses at crossover.

4.3.4.2 Overlapped spectral crossover (LF + HF)

Overlap-class spectral crossovers are often used to combine subwoofers and full-range enclosures, which may share the 60 Hz to 120 Hz range (again Fig. 4.26). The decision of when and where to use an overlapped crossover instead of unity is not clear-cut.

Overlap and unity crossover considerations

- Overlap increases efficiency and headroom in the affected range (drivers working the same range).
- Overlap narrows the coverage pattern (whether this is desirable is situation dependent).
- Overlap may cause increased combing in some locations (more so if the speakers are far apart).
- Overlap helps the sound image remain spectrally linked (subs not separated apart from mains).
- Operating a speaker into the overlap range may reduce the headroom of the individual drivers. The individual headroom loss may reduce the efficiency gain from the summation in the overlap zone.

The process is close to the unity crossover with an added equalization step.

Creating an overlapped crossover

- Determine a reference level: 0 dB.
- Set both the LF and HF cutoffs to create the target overlap range (e.g. 60–120 Hz). This may be unnecessary if the natural roll-offs give the desired response.
- Drive each speaker and observe the individual channel acoustic response.
- Adjust relative levels until they match in the crossover target range (turn down the louder one).
- Adjust relative phase to match as much of the crossover range as possible (delay the earlier one).
- Driving both channels together should create a +6 dB peak centered in the target range.
- Add a parametric filter (-6 dB at the center of the overlap) to both channels. Adjust bandwidth as required to normalize the response.

4.3.4.3 SELECTING THE CROSSOVER FREQUENCY

It is increasingly rare to encounter systems requiring field selection of the crossover frequency. This should never happen, but it does. Extensive R&D should go into the selection process, an unlikely scenario in the field with minutes ticking down until show time.

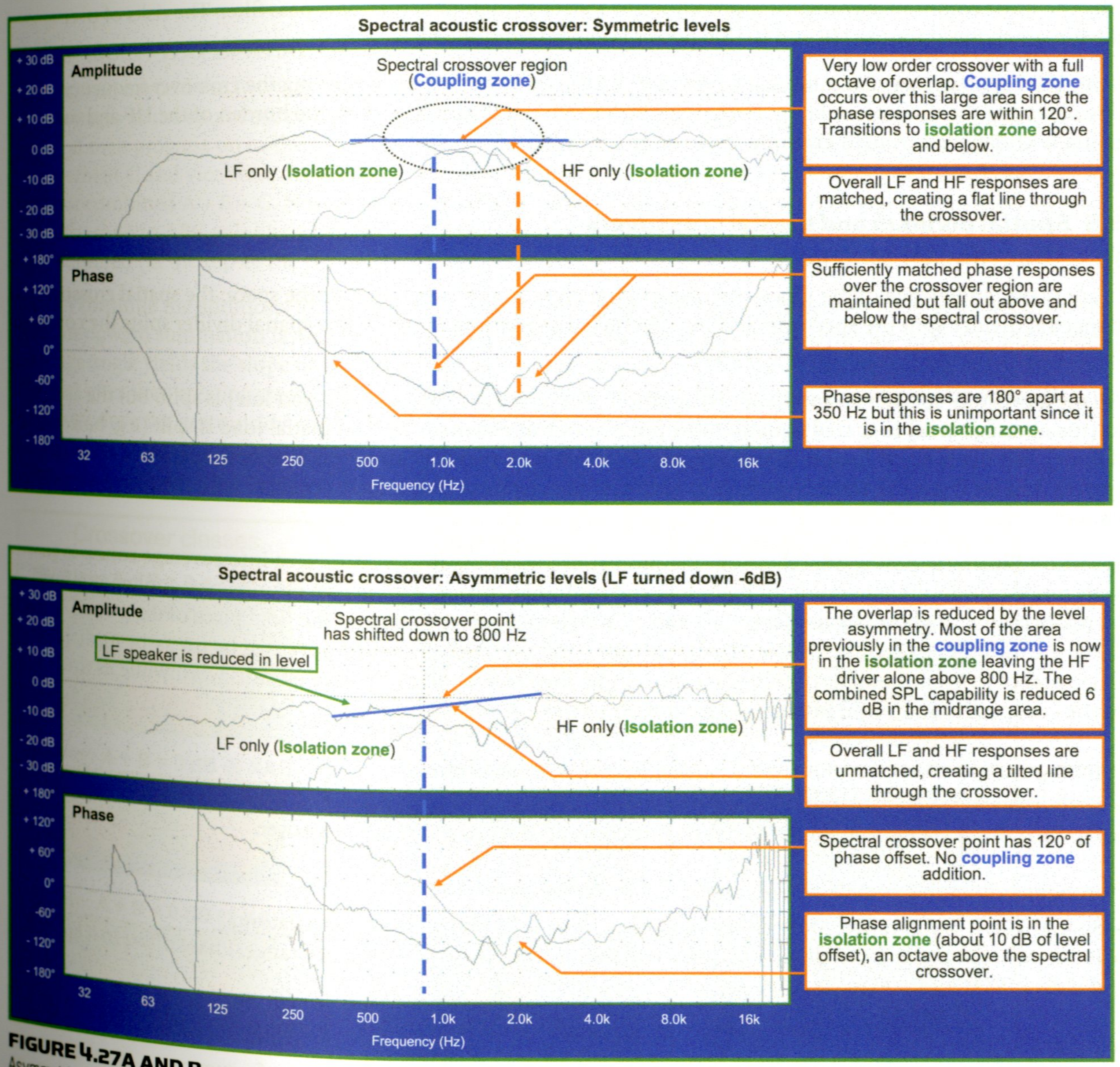
Crossover frequency selection considerations

- Optimal frequency range for each driver. Affects power capability, headroom, excursion and more.
- Polar responses of HF and LF components change over frequency. The rate of polar change through crossover may be affected. For example, HF horns tend to become wider as the cutoff frequency is lowered, whereas LF drivers narrow as the cutoff rises.
- Cutoff frequency selection has a significant impact on HF driver excursion. It's beyond the scope of this text, but basically amounts to this: Excursion rises exponentially as frequency drops. Halving the frequency requires quadrupling the excursion to produce the same acoustic power.
- Lowering a crossover frequency may cause the device to operate below the coupling range of the horn, lowering efficiency and requiring still more excursion to achieve the demanded SPL.

It's generally safer to run drivers above their operational range than below. Therefore a good starting point is to observe the upper limits of the raw LF response. The crossover must be below LF limit and see how high it can go. If we start the HF driver with an HPF set an octave below the prospective target we can see if the driver can make the meeting point. Then begins an iterative trial and error in the target range. Different slopes and topologies can be tried until the best fit is found. After aligning the crossover in the on-axis area it is suggested to move off axis to see how well the LF and HF patterns match. There's no way to practically perform a thorough R&D process in the field but this roughs things in when that is all we can do.

4.3.4.4 CROSSOVER AUDIBILITY

We generally seek to suppress clues that alert audiences to the presence of speakers. Violins do not have crossover frequencies. A multi-way speaker can reproduce the full range of the violin, but we must carefully handle the crossover region to ensure a listener does not notice the transition between drivers. One mechanism that can expose the driver transition is displacement. The probability of distinct localization increases as drivers move apart. This is not an issue for integral multi-way enclosures but can be for subwoofers, which are often a large distance apart from the mains. A second factor is overlap, which can expose the crossover transition by having too much or too little overlap. Crossovers with extremely steep filters can transition in a single note of the musical scale. This becomes most audible if the transition moves between elements with large differences in pattern control, e.g. a front-loaded cone driver to a narrow horn. The reverberation character can suddenly change with the transition. On the other hand, with excessive overlap, the filters won't isolate enough to prevent combing around crossover. This leaves the transition exposed by the presence of dips in the response above or below the crossover frequency. A final example



Very low order crossover with a full octave of overlap. **Coupling zone** occurs over this large area since the phase responses are within 120°. Transitions to **isolation zone** above and below.

Overall LF and HF responses are matched, creating a flat line through the crossover.

Sufficiently matched phase responses over the crossover region are maintained but fall out above and below the spectral crossover.

Phase responses are 180° apart at 350 Hz but this is unimportant since it is in the **isolation zone**.

The overlap is reduced by the level asymmetry. Most of the area previously in the **coupling zone** is now in the **isolation zone** leaving the HF driver alone above 800 Hz. The combined SPL capability is reduced 6 dB in the midrange area.

Overall LF and HF responses are unmatched, creating a tilted line through the crossover.

Spectral crossover point has 120° of phase offset. No **coupling zone** addition.

Phase alignment point is in the **isolation zone** (about 10 dB of level offset), an octave above the spectral crossover.

FIGURE 4.27A AND B
Asymmetric-level spectral crossover example

is the combination of both displacement and minimal overlap in the case of grounded subs and flying mains. Both factors emphasize separation, which can be experienced as two distinct sources.

Let's set a goal of minimum "crossover detectability": driver transition without anyone noticing. Minimal displacement, minimal coverage angle transition, minimal combing and more gradual filter slopes have the highest prospects of slipping under our sonar. Our hearing mechanism clues in on abrupt changes in sonic character between notes. Displacement causes an abrupt change in localization. Combing causes an abrupt change in level as one note disappears and the next returns. Coverage angle transition causes a change in the reverberant field, leading the listener to feel as if one frequency is far away in a reverberant space while the next is nearby in a dry space.

4.3.4.5 CROSSOVER ASYMMETRY

Different filter slopes make the transition from coupling to isolation asymmetric. Asymmetric slope rates can be used effectively, but their action must be anticipated. The mixing of even and odd filter orders (e.g. second order and third order) usually requires a polarity reversal and mismatched corner frequencies to achieve a unity crossover result. The most common asymmetric slope choice is a steeper high-pass than low-pass filter. The risks of over-excursion are reduced for the HF and usable power is shared from the LF.

Relative-level settings can also introduce asymmetry in the crossover range, by shifting the crossover frequency and reallocating the division of labor. Dropping the level of the LF driver adds to the burden of the HF and can potentially endanger it. A field example is shown in Fig. 4.27.

4.3.5 Spatial dividers and spatial crossovers

4.3.5.1 SPECTRAL VS. SPATIAL

Let's apply our knowledge of the phase-aligned spectral crossover to coverage over the space: the spatial crossover. The spectral divider split the spectrum and the spectral crossover joined them. The spatial divider splits the coverage and the spatial crossover joins them together.

Let's take a two-way speaker as an illustrative example. The spectral load (e.g. high and low) is split, but the spatial load (the coverage area) is shared equally. Now put two of these in an array. The spatial load is split (e.g. balcony and floor), but the spectral load is shared equally. Our two-way, two-way array contains both species of acoustic crossover, and we'll use the same approach to optimize the response in the most sensitive area: the phase-aligned crossover.

This section illustrates how spatial division, the process of separating the listening area into coverage zones, is so directly analogous to the separation of high, low and midrange drivers. A single set of principles applies to a four-way crossover in a single enclosure (spectral) and a four-element array (spatial). The final piece of the puzzle is the walls of the room. They are the ultimate spatial dividers and their reflections are governed by the same principles. The revision of conventional terminology requires some time to assimilate, but the effort is worthwhile as the mysteries of speaker and room interaction yield their secrets.

Common ground between spectral and spatial acoustic crossovers

- Both interactions are governed by the properties of acoustic summation.
- Optimization strategies are rooted in the same concept: the phase-aligned crossover.

Differences between spectral and spatial acoustic crossovers

- Spatial XOVR is full range. More challenging to achieve isolation without cancellation.
- Phase offset in the spectral divider strongly affects only the crossover frequency range. Phase offset in a spatial divider affects all frequencies.

Analogous functions

- Coupling zone location (speakers at equal level) is analogous to spectral crossover frequency.
- Directivity is analogous to filter slope. Highly directional speakers are like steep filters.

- A change in relative level between speakers shifts the spatial crossover location just as it shifts the spectral crossover frequency.
- Power addition from horizontal or vertical overlap in the spatial crossover is analogous to the addition from overlap in the spectral crossover.

Spatial acoustic crossovers are more complex than their spectral counterparts, yet are variations on the same themes (Fig. 4.28). Place two matched speakers in any orientation and find the mid-point between them. That's the crossover point and the coupling zone for all frequencies. The next part is a little harder. Now we have to find our way out of there to the isolation zone: the position where one speaker is 10 dB more dominant in level. This is easily found for a single frequency by observation of the coverage patterns. The break point into the isolation zone would be as simple as the spectral filter slopes *if* the speaker has the same directional pattern for all frequencies. This is as likely as spotting a unicorn. In the real world the low frequencies will typically overlap much more than the highs, giving us different points in the room for the borders of the coupling, combing, transition and isolation zones over frequency.

4.3.5.2 MULTI-WAY SPATIAL CROSSOVER

Let's expand beyond the two-way (A + B = AB) crossover by adding a third element (C). The summation progresses in two stages as the sound propagates forward: (A + B) + (B + C) = ABC (Fig. 4.29). The adjacent summations occur first and then progress on to the full three-way combination, i.e. element A will close the gap with B before it has met element C and vice versa. At this stage we have two isosceles triangles, side by side. Stack a third one on top and we have combined A + B + C. Notice we've started a pyramid. If the AB and BC gaps closed at 1 m, then the meeting point for the trio ABC will likely be 2 m. The array assumes its permanent far-field shape once all elements have fully summed (at the top of the pyramid).

We can continue the additions for as long as the budget and rigging allows. Each new element expands the base and adds an upward summation layer. Element spacing sets the foundation size of the pyramid base, and the element coverage angle yields the slope of the sides. Narrow elements take longer to meet their next-door neighbors and the next after that, creating steeper triangulation and pushing the far-field response transition into outward. Wide elements close the gap quickly and finish their shaping closer to the sources.

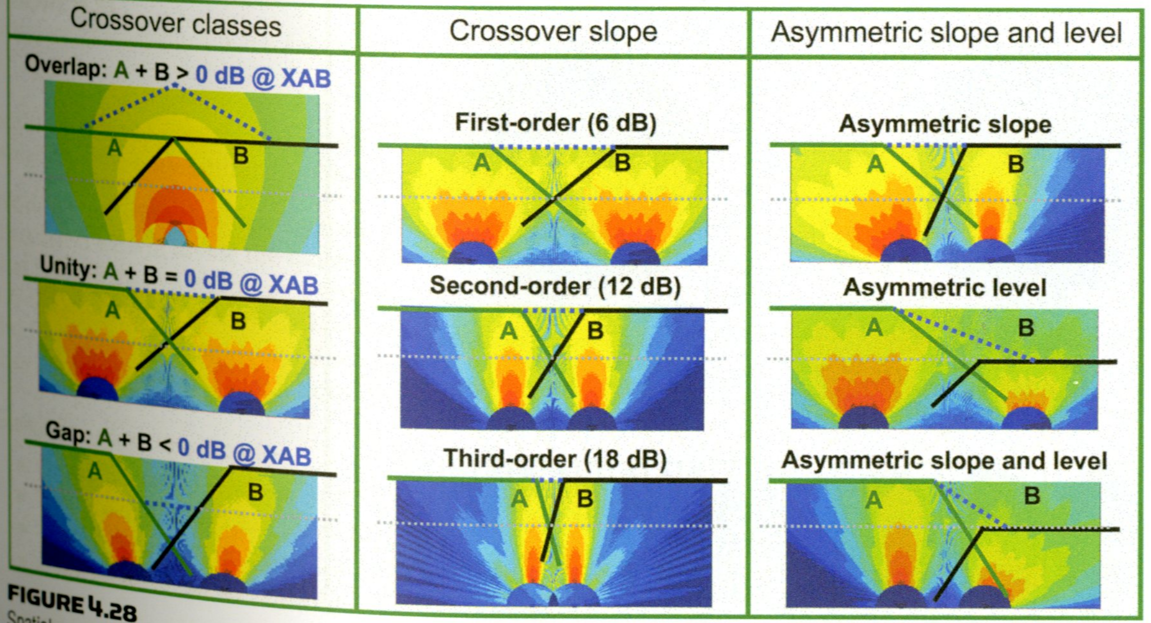


FIGURE 4.28
Spatial crossover classes, slope and asymmetry. Note the analogous relationship to the spectral crossover in Fig. 4.23.

The pyramid is clearly evident when element spacing is close enough to maintain coupling. By contrast, widely spaced elements will comb with their many neighbors rather than couple. The upper summation layers will look more like a fireworks finale than a pyramid. Could we call it comb-bustion? We can't stop the upper layer combing, but we can make it irrelevant by sending in other speakers to take over the coverage. Every seat in the hall can see all of the frontfills. The reason their upper-layer combing doesn't bother us is because we pave over them with the mains.

4.3.5.3 SPEAKER ORDER (CROSSOVER SLOPE)

A big step in transferring our spectral knowledge to the spatial domain is to visualize speaker coverage pattern as a form of spatial filtering (Fig. 4.30). A 360° speaker is as spatially "full range" as one covering 20 Hz to 20 kHz is spectrally. A spectral range of 10 octaves is analogous to a spatial range of 360°. If we straighten out the radial circle we can lay the two shapes side-by-side. A two-way system splits the coverage (2 × 5 octave or 2 × 180°) or we can go three-way (3 × 3.3 octave and 3 × 120°). We can go on slicing like this forever. We know from spectral crossover experience we need steeper filters on a four-way system than a two-way. An eight-way? Even more. Steeper filters isolate the more closely spaced signals. Same with spatial filters. If we're slicing coverage in 20° segments, they need to be steep to prevent excess overlap into neighboring areas. We don't always need to cover 360° any more than we always need to cover 20 Hz–20 kHz, but if we want to slice things into small bits, then steep filters are the most effective means of getting to the isolation zone and minimizing combing.

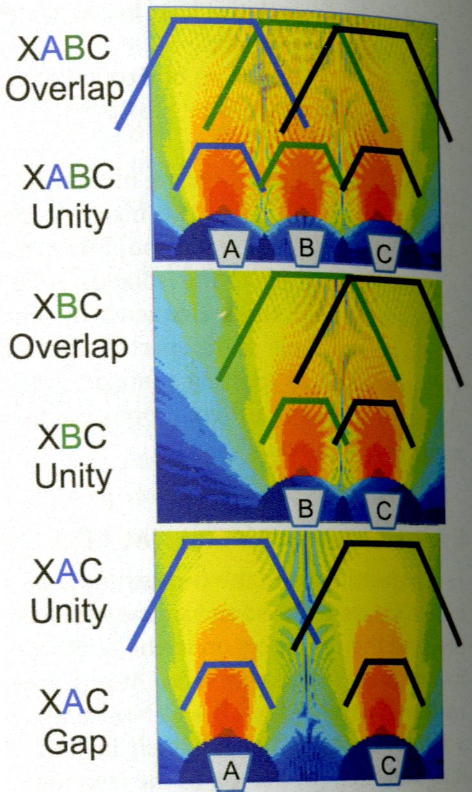


FIGURE 4.29
Multi-way spatial crossover

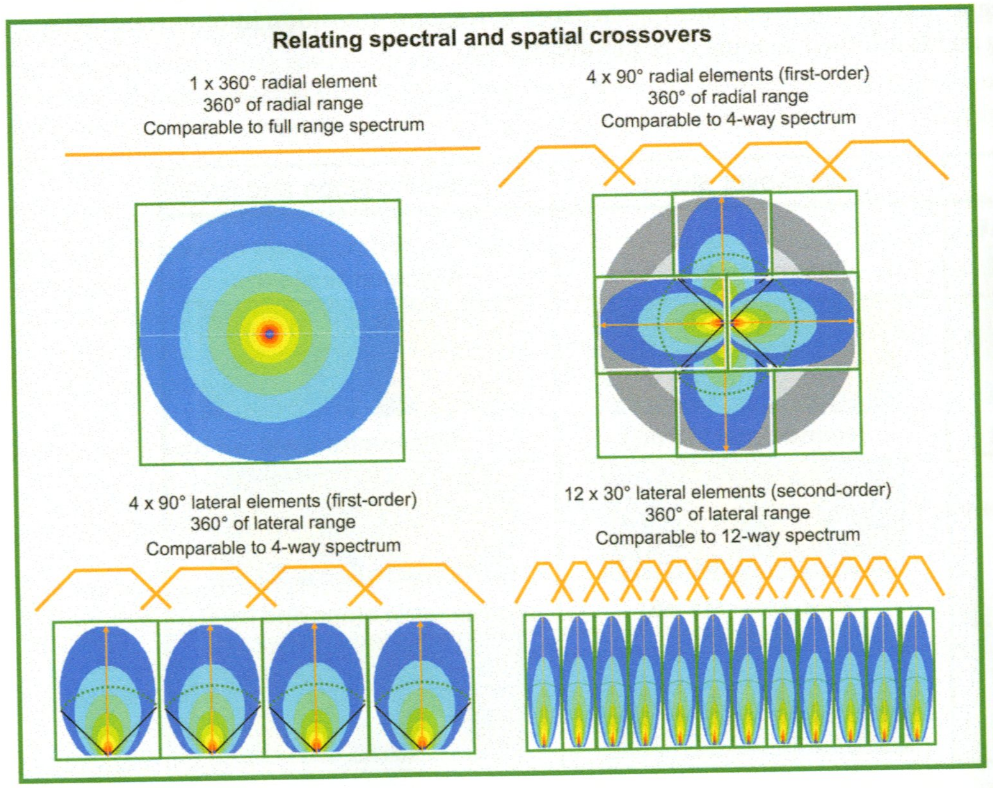


FIGURE 4.30
Linking the spectral and spatial orders: 1 × 360°, 4 × 90°, 12 × 30°

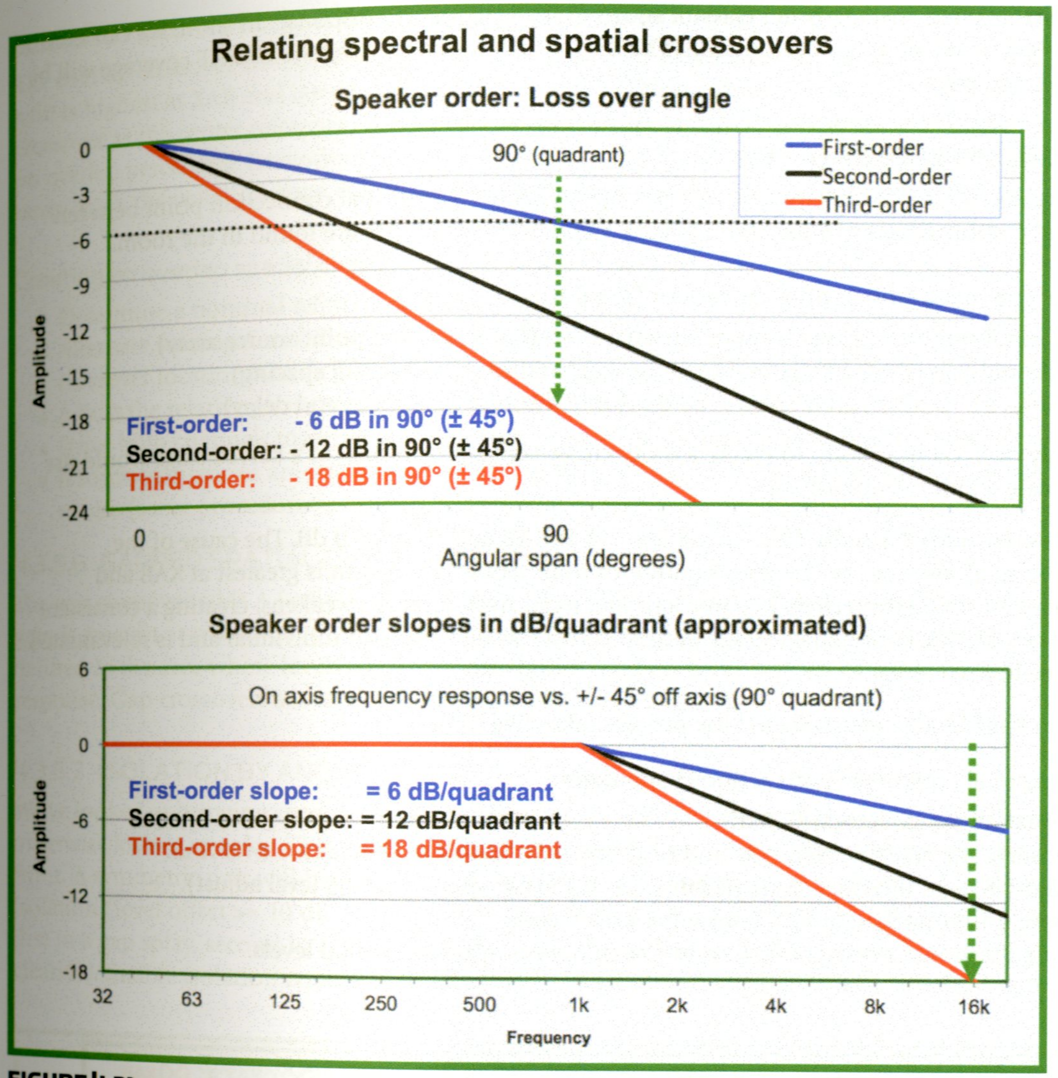


FIGURE 4.31
Linking spectral and spatial crossovers: first order, second order, third order

We don't use 360° speakers any more than we use a single driver to cover 20 Hz–20 kHz. For purposes of discussion we will divide the space into quadrant slices (90°) and classify coverage from there (Fig. 4.31). A speaker that loses -6 dB in a quadrant is termed a first-order speaker (analogous to -6 dB/octave). One that falls at a rate of 12/dB per quadrant is second order and so on. By classifying the speakers into first, second and third order (as we did filters) we can simplify our discussion of speakers, emphasizing the basic shapes they make rather than whether they are front-loaded, a radial horn, a ribbon, or a retro-encabulator waveguide.

Speaker order classification

- Omnidirectional: 180° to 360° (< 6 dB loss in a 90° quadrant).
- First order: 60° to 180° (around 6 dB loss in 90°).
- Second order: 20° to 60° (around 12 dB loss in 90°).
- Third order: 6° to 20° (around 18 dB loss in 90°).

A given speaker may have different coverage patterns in the vertical and horizontal planes, hence different orders. In addition we know that coverage patterns widen in the LF range, so a single classification will not represent the full range of speaker behavior. We use speaker-order classifications to separate the HF response. In short, we can assume that every speaker will end up omni at the bottom end. The disparity between LF coverage and HF coverage will be greatest in the third-order speakers.

4.3.5.4 UNITY SPATIAL CROSSOVER (A + B)

The unity gain spatial crossover is a mainstay of design and optimization, a principal connection point between speakers in an array and combinations of subsystems (Fig. 4.32). Three main types are found in the room.

Three typical forms of the unity gain spatial crossover (A + B)

- Unity splay angle: -6 dB point is created by angular separation (e.g. a coupled point-source array).
- Unity spacing: -6 dB point is created by lateral or vertical separation (e.g. frontfill spacing).
- Unity distance (forward): -6 dB point is created by doubling distance (e.g. main and delay).

These can be used singly or in combination to create a unity crossover (e.g. frontfills on a curved stage would use splay *and* spacing to create a unity summation).

The standard unity crossover adds A (-6 dB, 0°) + B (-6 dB, 0°) at XAB and sums to 0 dB. The cause of the individual losses may be axial, distance or the combination of both. Summation gain is greatest at XAB and weakens away from there. Individual speakers become stronger as summation gain weakens, creating a consistent level while moving off center. The summed coverage pattern is twice as wide as each individual and is re-evaluated using crossover as the center reference.

If the crossover location has already been selected the process takes five steps.

Creating a unity gain spatial crossover with A and B speakers

- Determine a nominal reference standard: 0 dB.
- Drive A (solo). Observe the acoustic response and find the -6 dB location. This is crossover XAB.
- Drive B (solo). Adjust B until it creates -6 dB at same location (e.g. splay, spacing, level adjust).
- Adjust relative phase until matched at XAB (delay the earlier one).
- Drive A + B. Summed response at crossover should match the nominal individual levels.

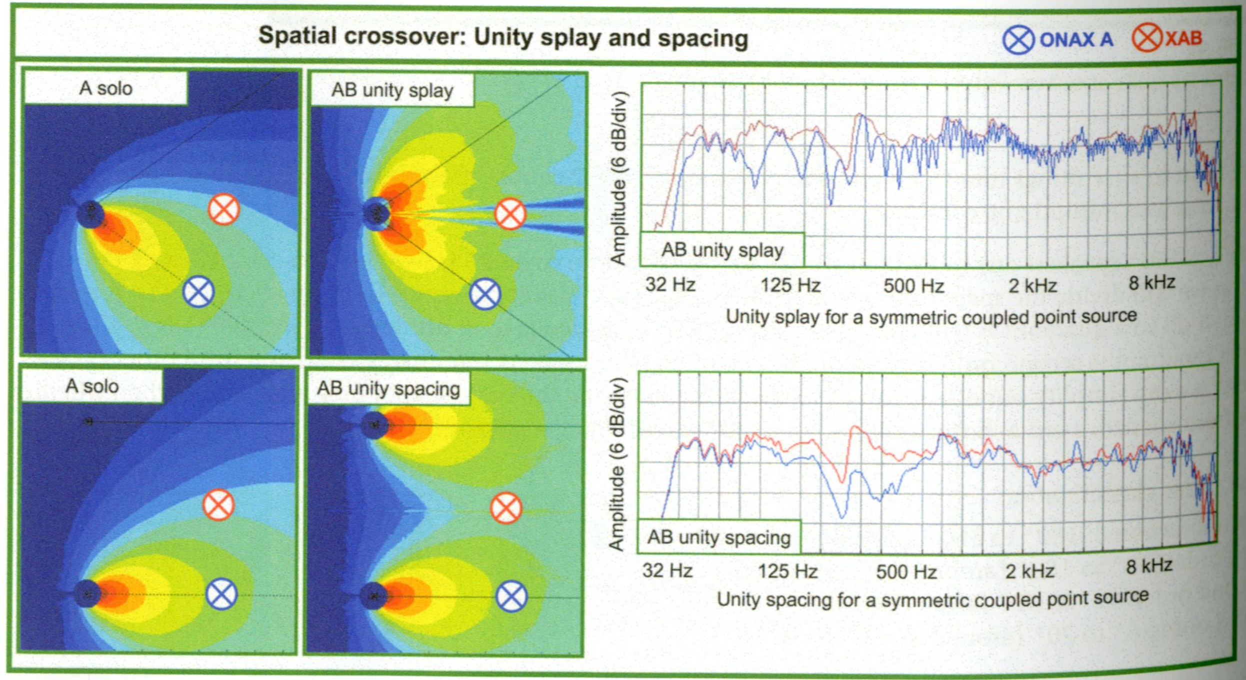


FIGURE 4.32
The unity spatial crossover

4.3.5.5 OVERLAPPED SPATIAL CROSSOVER (A + B)

The overlap crossover adds A (>-6 dB, 0°) + B (>-6 dB, 0°) at XAB and sums to >0 dB (+6 dB max). Summation gain is highest at XAB and lessens off center (Fig. 4.33). The summed coverage pattern is re-evaluated using crossover as the center reference. The combination is wider, narrower or the same as individual elements, depending on overlap percentage (majority overlap narrows, majority isolation widens). Highly overlapped systems might never reach the isolation zone (level offset doesn't reach 10 dB).

Creating an overlap spatial crossover with A and B speakers

- Determine a nominal reference standard: 0 dB.
- Alternate soloing A and B to find the equal-level location (matched at >-6 dB from the reference level). This is crossover location XAB (e.g. if the A and B levels are -2 dB then the summation will be +4 dB).
- Adjust the relative phase until they match at XAB (delay the earlier one).
- Drive both channels together. Summed response should exceed the individual levels by +6 dB.
- If some frequencies are overlapped and others are not, then equalization can be applied to the overlapped ranges (same procedure as overlapped spectral crossovers).

4.3.5.6 GAPPED SPATIAL CROSSOVER (A+B)

The gap crossover adds A (<-6 dB, 0°) + B (<-6 dB, 0°) at XAB and sums to <0 dB (Fig. 4.33 again). Summation gain is greatest at crossover and lessens off center (whereas individual levels get stronger). The gapped zone is defined as the area where levels are below the 0 dB reference. Gaps of 6 dB or more are equivalent to off-axis response. Gap crossovers are used to avoid areas such as balcony fronts.

4.3.5.7 ISOLATION BY ANGLE

We've looked at bringing speakers together. Now we'll evaluate getting them apart. The first way is angular isolation, otherwise known as splay. This method is implemented in the point source array by aiming the speakers apart in front. A symmetric pair will have a centered crossover, which may be overlapped, unity or gapped. The road to isolation (level offset >= 10 dB) begins at crossover and heads toward the outer edge of the coverage. We reach it first in a gap splay, second in a unity splay and last (if at all) in an overlap splay. The coupled point source has a clearly definable isolation zone: A given frequency has a certain angle at which isolation occurs, an angle that holds

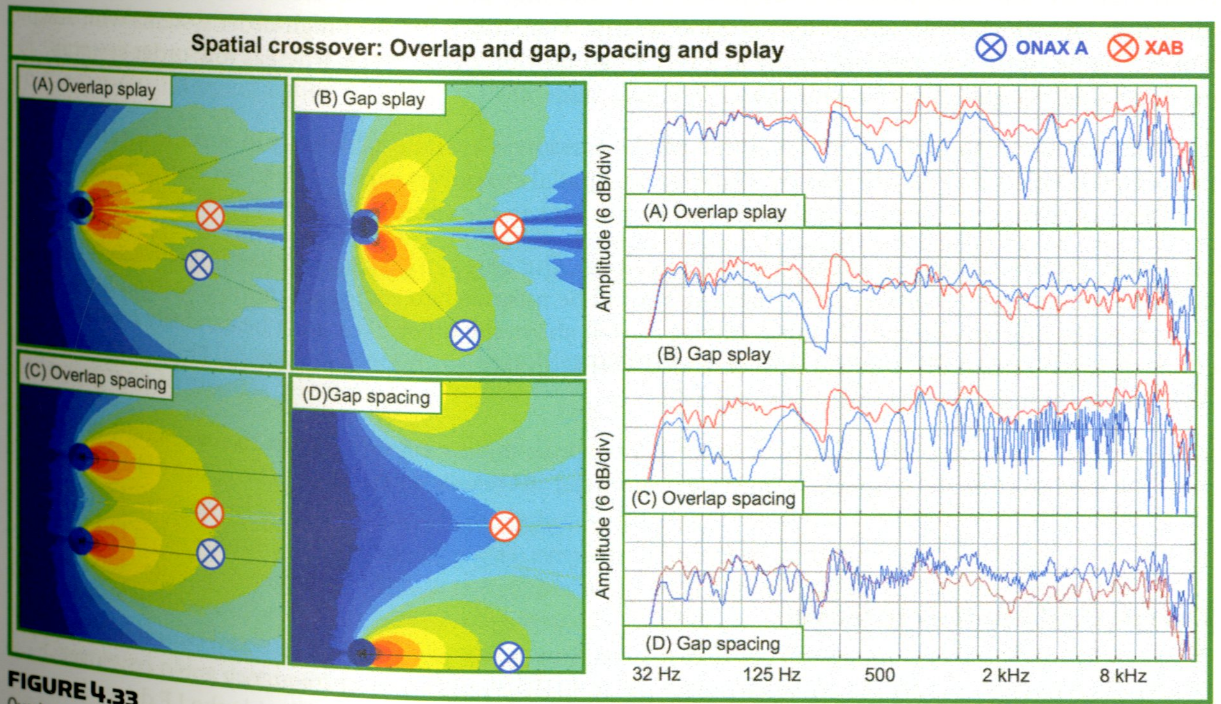


FIGURE 4.33
Overlap and gap spatial crossovers

over distance. For example, if isolation at 8 kHz begins at 20° away from crossover, it will (a) hold the same level of isolation over distance and (b) be more isolated at angles further away from crossover.

4.3.5.8 ISOLATION BY DISPLACEMENT

The next avenue toward isolation is separation/displacement. Move speakers far apart and they must cover a lot of ground before they can connect. This is an uncoupled array configuration, and therefore will morph through different summation zones over distance. A simple example: Two speakers are placed 10 m apart. If we walk a straight line from the front of A (at 1 m) to the front of B (at 1 m) we will move from isolation (A) to a gap (XAB) to isolation (B). The same path at 20 m in front of the speakers will be constant overlap (and combing). At some distance between we can walk a line and go from isolation (A) to unity (XAB) to isolation (B). In front of the unity line is too close (pre-coverage), and past it is too far (post-coverage). Our goal will be to close the gap at the right place, and conduct damage control on the overlap. Wide spacing of narrow elements would maintain isolation the longest, and close spacing of wide elements the least.

4.3.5.9 ISOLATION BY LEVEL

We can shift the summation zone balance by leaving speakers in position and turning one down. The crossover location will move toward the lesser speaker (B). Think of the level reduction as the B speaker yielding territory to A, an asymmetric-level distribution. On the A side we'll see isolation arrive sooner (because B will more quickly fall 10 dB behind), whereas the inverse is true for the B side.

4.3.5.10 ISOLATION BY COMMITTEE

All the isolation mechanisms just listed can be brought together to create the desired shaping. We can move them apart, splay them apart and turn one down. The transition to isolation comes quickly for the dominant speaker. For the smaller one, welcome to life as a fill speaker.

4.3.5.11 CROSSOVER DETECTABILITY

Hiding spatial dividers is challenging because the crossover frequency range extends to the upper limits. It's virtually impossible to transition through crossover without some HF combing. Spatial crossovers can have substantial physical displacement, which makes the combing zone volatile. Transitions between high-order systems with steep angular slopes may be easily detectable but only in a very small portion of the space, whereas low-order systems will be less detectable, yet spread over a wider space. A classic tradeoff.

The most salient contrast to spectral crossovers is that spatial crossovers are detectable only in specific locations. Detectable spectral dividers may be obvious over large areas. Spatial crossovers can be placed on aisles, balcony fronts and other places that render their deficiencies academic. Not so the spectral divider.

The spatial divider gives itself away by shifts in angular position. Our ears can pick up localization clues, which become easier to spot as angular offset rises. Other clues could be mismatched responses in the crossover area. The most obvious is when one speaker has HF range extension well above the other. This must be carefully managed when combining small-format fill speakers with extended VHF with large-format main systems. The mixer won't hear the VHF in the frontfills but the first row surely will.

Another clue comes in the form of the relative distance. Close speakers have superior direct-to-reverberant ratio over distant ones. The level of close delay speakers must be minimized so they don't stand out above the distant main speaker.

4.3.6 The spectral/spatial crossover

Most of the two-way loudspeakers in the world have displaced drivers: HF next to LF or centered between two woofers. The spectral crossover is also a spatial crossover. LF and HF have a crossover frequency and a crossover location (Fig. 4.34). The exception is the coaxial design, where the HF driver is centered inside the LF driver (in which case the displacement is in the depth plane rather than horizontal or vertical).

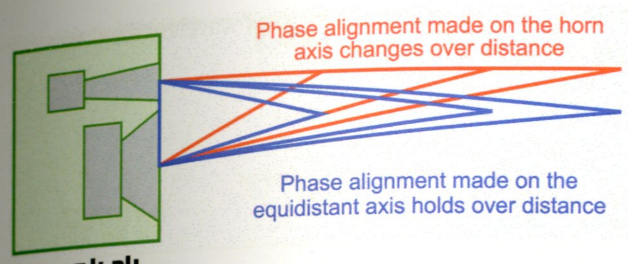


FIGURE 4.34
Spectral/spatial crossover

This adds a second dimension to the quest for combing-free crossover performance. The goal is to stay in the coupling zone until we are out of the angular coverage, i.e. spectral coupling until spatial isolation. We return to the isosceles triangle (our representative of the spatial coupling zone and target for phase alignment). We can view the drivers as a spatial crossover and align the spectral level and phase by the unity spatial crossover procedure outlined previously (4.3.5.4).

Spatial stability is evaluated by measuring off center of the crossover (above and below or side to side). Observe the crossover frequency range and see if the response holds out long enough to reach the spatial coverage edge. This is best done at a distance long enough to represent real-world applications. This allows the time offsets to settle into the range where the speaker will actually be used. Measuring too close can make a perfectly functional spectral/spatial crossover appear troubled.

4.4 SPEAKER ARRAYS

Let's apply our study of summation and the acoustic crossover to the practical construction of speaker arrays. Add two speakers and the sum will depend on their level and phase offsets. Add ten speakers and they will behave exactly as the summation of the summations. The individual element coverage patterns, their displacement, relative angles and levels drive the spatial distribution. If we successfully merge the systems at the spatial crossovers, the rest of the coverage area will become predictable and manageable. All of these factors can be independently controlled in the design and optimization process.

4.4.1 Speaker array types

The pro audio trade news would lead us to believe there are hundreds of different speaker array types, with various trademarked™ names. Others believe that there is only one array type, the line array, and all other configurations have gone the way of the dinosaur.

In practical terms we classify arrays into two families of three types. First we separate coupled from uncoupled and then move on to angular orientation.

Array Type	**Configuration**
Coupled line source	Speakers together in parallel
Coupled point source	Speakers together with outward splay angles
Coupled point destination	Speakers together with inward splay angles
Uncoupled line source	Speakers separated in parallel
Uncoupled point source	Speakers separated with outward splay angles
Uncoupled point destination	Speakers separated with inward splay angles

How do we separate coupled from uncoupled? It's harder than you think. The 600:1 ratio of wavelengths these arrays transmit makes the gray become grayer. The easiest way to clarify is by function.

Coupled array functions	**Uncoupled array functions**
Power gain	Radial coverage expansion
Radial coverage expansion	Lateral coverage expansion
Radial coverage reduction	Forward coverage expansion

Power gain requires coupling zone summation, as does radial coverage narrowing. Radial and lateral coverage expansions require isolation zone summation. The transition zone is the preferred bridge between coupling and isolation whereas the combing zone is to be avoided as much as possible.

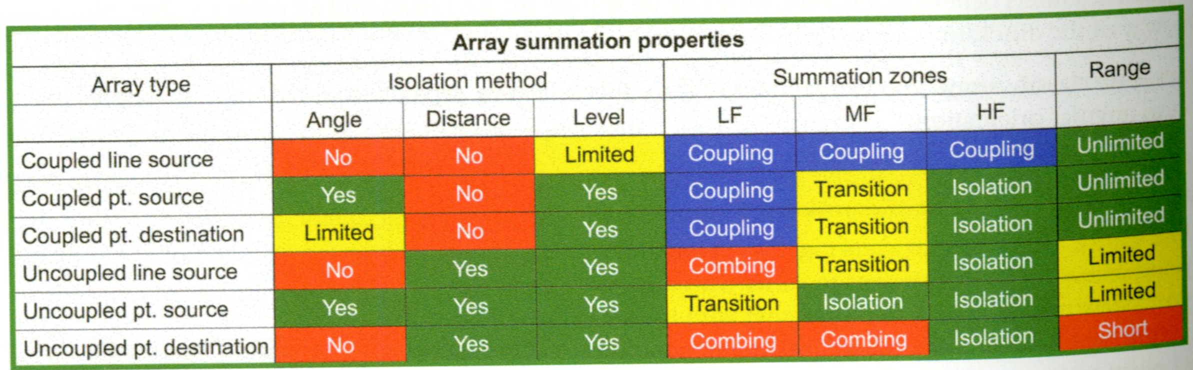
Let's return now to the coupled/uncoupled question. As an example we have a straight line of eight subwoofers spaced 1 m apart. On top of each is a small full-range frontfill. We have both a coupled and uncoupled array. The quantity of eight subwoofers adds power gain and narrows coverage. The quantity of eight frontfills creates a lateral coverage expansion. If we need more LF power we add subs. If we need more frontfill coverage we add frontfills. If we need more frontfill power we get a bigger frontfill. Coupled vs. uncoupled.

Any speaker array can create a coupling zone along the coverage centerline (the isosceles triangle). Closely spaced arrays can maintain the coupling for a substantial portion of the spectrum *and* the room. Adding space between the elements lessens coupling in both. We can rescale our arrays, but not the size of 500 Hz. We conclude the obvious: Coupled arrays have superior coupling zone behavior. Duh!

Once we run out of coupling capability we seek isolation, which we can get by angle, spacing or level. Angle is the most effective and long lasting. Isolation by displacement is effective, but as advertisers love to say "for a limited time only!" Level tapering, on its own, is the most limited, and should be considered more as an addendum to isolation than a primary means. We can use them together to great effect.

Which arrays can isolate? The point source is the master of angular isolation. The line source has none. The point destination can provide angular isolation after its beams have passed through the center. This gives it limited applicability. The uncoupled arrays are the winners for displacement isolation. Any array can taper level, but this is not much help without a head start from angle or displacement.

Let's look at the scorecard (Fig. 4.35). One array configuration provides extensive coupling and long-range isolation: the coupled point source. It's no coincidence that this is the main array used in most sound reinforcement systems. The coupled point destination can also provide both but runs into mechanical challenges such as speakers blocking other speakers from crossing through to the opposite side. The coupled line source has no effective isolation mechanism. The result is a concentrated beam focused at infinity.



Array summation properties

Array type	Isolation method			Summation zones			Range
	Angle	Distance	Level	LF	MF	HF	
Coupled line source	No	No	Limited	Coupling	Coupling	Coupling	Unlimited
Coupled pt. source	Yes	No	Yes	Coupling	Transition	Isolation	Unlimited
Coupled pt. destination	Limited	No	Yes	Coupling	Transition	Isolation	Unlimited
Uncoupled line source	No	Yes	Yes	Combing	Transition	Isolation	Limited
Uncoupled pt. source	Yes	Yes	Yes	Transition	Isolation	Isolation	Limited
Uncoupled pt. destination	No	Yes	Yes	Combing	Combing	Isolation	Short

FIGURE 4.35
Array summation properties

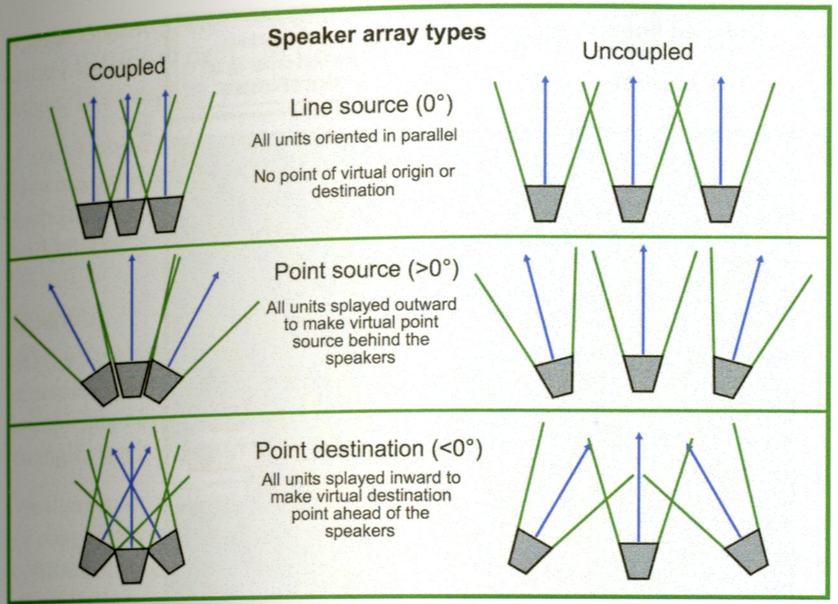


FIGURE 4.36
Speaker array classification

On to the uncoupled arrays where the point source isolates by a combination of displacement *and* angle. This gives it an extensive usable range (both spectral and spatial). The uncoupled point destination is a tug-of-war between isolating displacement and de-isolating inward angle. This is the most limited in range of the uncoupled arrays. The uncoupled line source falls in the middle between the point source and destination.

The next step will be a spatial distribution study of the six array types (Fig. 4.36).

4.4.2 Coupled arrays

The analysis will focus on the far-field response, where the combination of multiple elements is fully matured. Long arrays with many elements may show near-field isolation due to displacement until the gap closes and all elements are summed. The forward distance required to reach maturity will vary with frequency (ranges with wider coverage will close sooner than those with narrow coverage). The response is shown in the 100 Hz, 1 kHz and 10 kHz format, which is used for the rest of this chapter. This series brings together the summation icons presented earlier and gives them context with the spatial crossover locations.

4.4.2.1 COUPLED LINE SOURCE

Coupled line source arrays allow unlimited element quantity at the most limited angle quantity: one. There's no simpler array to describe. No angle details, only element coverage pattern, quantity and displacement. The virtual sound source is elongated, stretched over the array length rather than a single point. The consistent feature of the coupled line source is that overlap class behavior comprises virtually the entirety of the system's response. This is both its most attractive and most ominous feature. The overlap gives it the maximum power addition, but at the cost of minimum uniformity.

Speaker order

The first in this series is Fig. 4.37, where we see the results of a pair of first-order speakers arrayed as a coupled line source. It's a train wreck. The only position to enjoy a ripple-free frequency response is the exact centerline: the

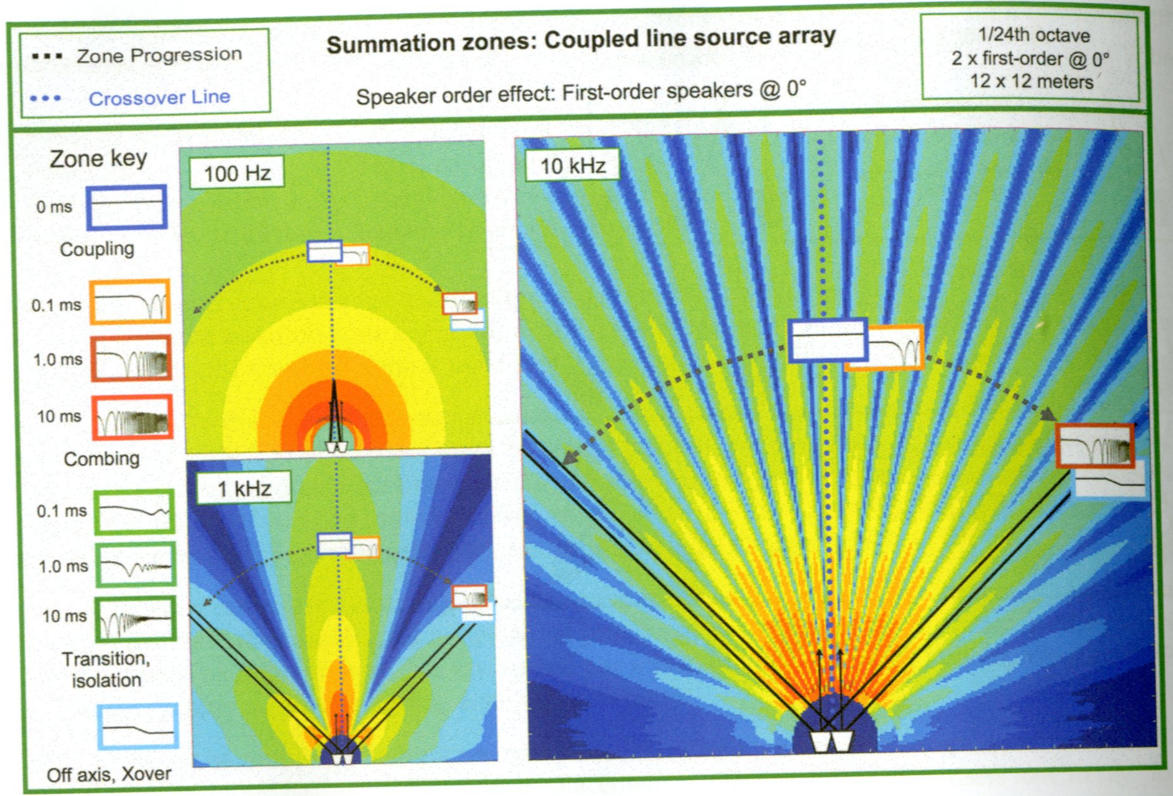


FIGURE 4.37
Summation zone progression factors for the coupled line source array, first-order speakers

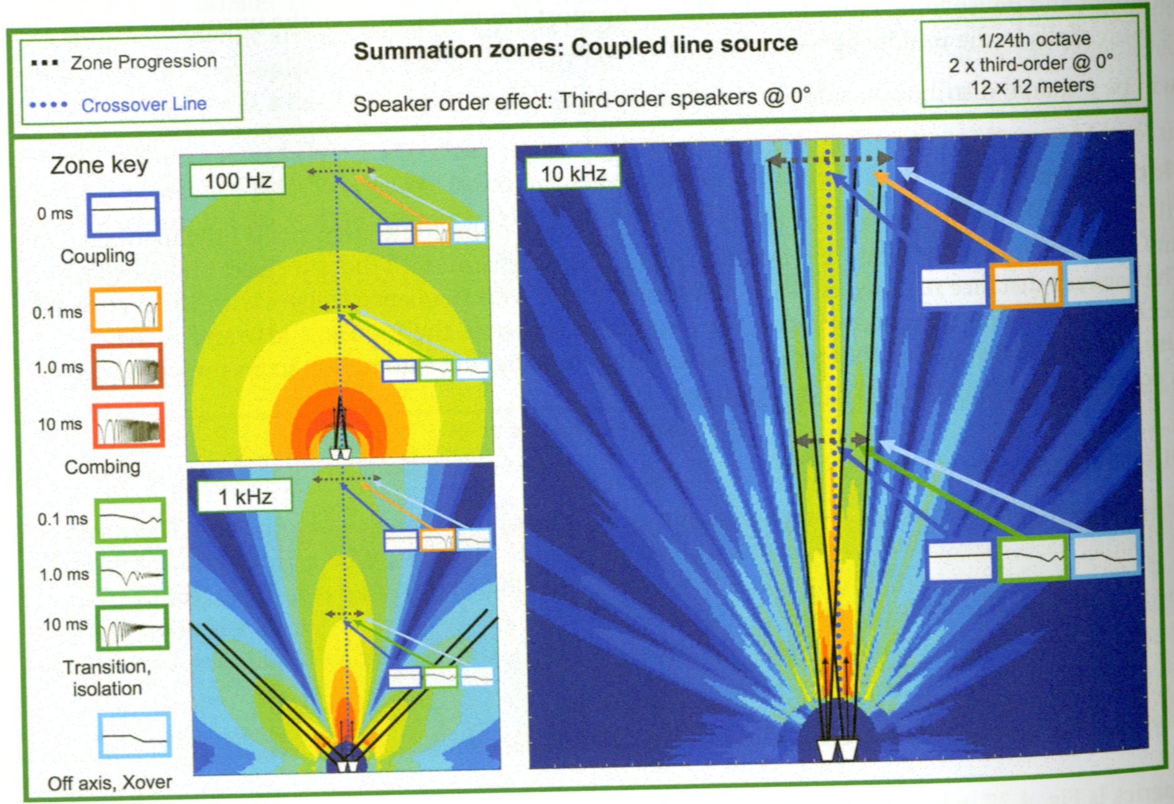


FIGURE 4.38
Summation zone progression factors for the coupled line source array, third-order speakers

spatial crossover, the result of excessive overlap and displacement. The summation zone progressions move from center to left and right. The combing zone dominates in the 10 kHz range, both near and far all the way to the edges. The coupling zone dominates the LF range due to close proximity.

A pair of third-order elements is seen in Fig. 4.38. The individual high-frequency coverage is so narrow that the gap coverage zone can be seen in the near field. This quickly gives way to overlap coverage where three beams can be seen (the main lobe and two side lobes). Notice the lack of uniformity over frequency, with extremely narrow HF and extremely wide LF response (just like the solo element).

Quantity

Maybe we just need more boxes. An additional third-order element is added in Fig. 4.39, extending the gap crossover range into two sections. It does little to address the discrepancy between the HF, MF and LF shapes. The complexity of the triangulation geometry increases with the addition of the third element. There are now multiple triangles stacked together, which increases the overlap with distance, narrowing the coverage angle.

We digress for a moment to address the coupled line source's fundamental property: the pyramid-shaped series of coupling zone summations. The pyramid effect comes from the cascading summations (Fig. 4.40). The phase contours of the three elements converge initially into two zones of addition (and one of cancellation). As we move farther away the three phase responses converge to form a single beam, the pyramid peak. Once the pyramid assembly is complete, the coupled array will assume the characteristics of a single speaker: a definable ONAX, a loss rate of 6 dB per doubling and a consistent coverage angle over distance. These milestones aren't found until the array has fully coupled (the pyramid top), which will make it challenging to place mics for optimization.

An eight-way line source pyramid is shown in Fig. 4.41. The foundation begins with the isolated elements (the gapped crossover) and then continues with seven twoway overlapping crossovers until it eventually converges into a single eight-way overlapped coupling zone summation. The distance to the first pyramid step (the two-way

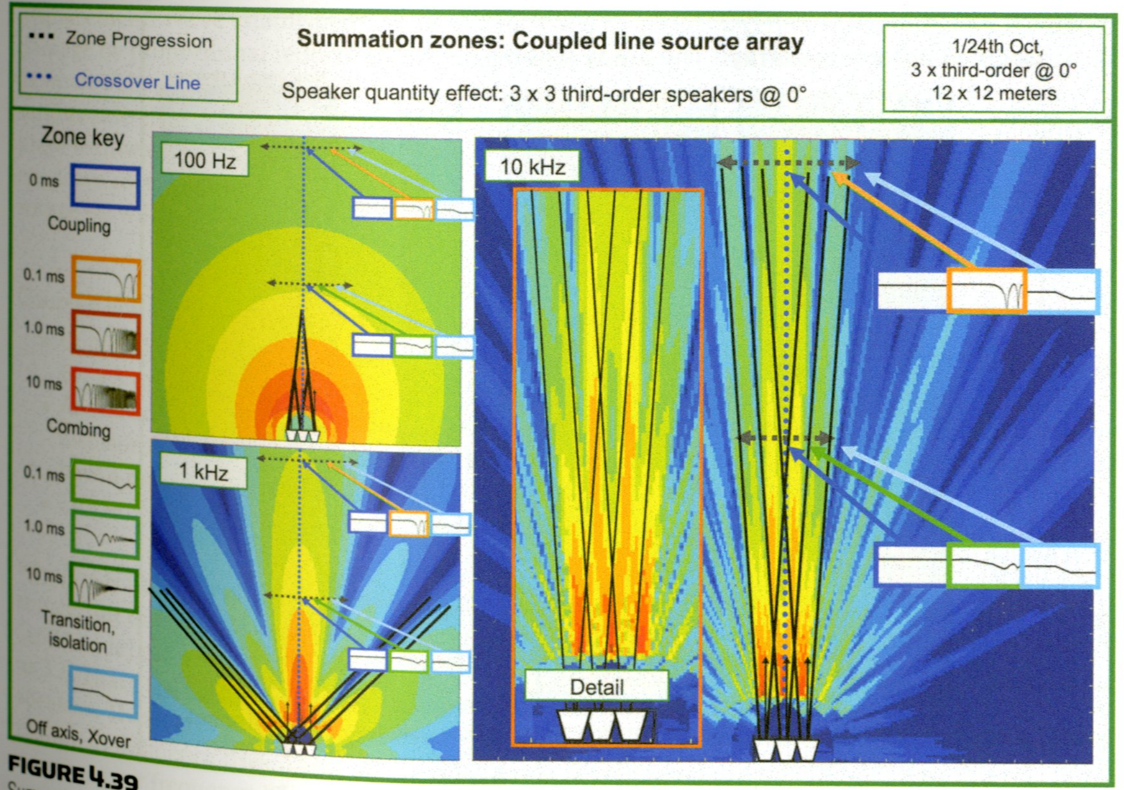


FIGURE 4.39
Summation zone progression factors for the coupled line source array, change of quantity

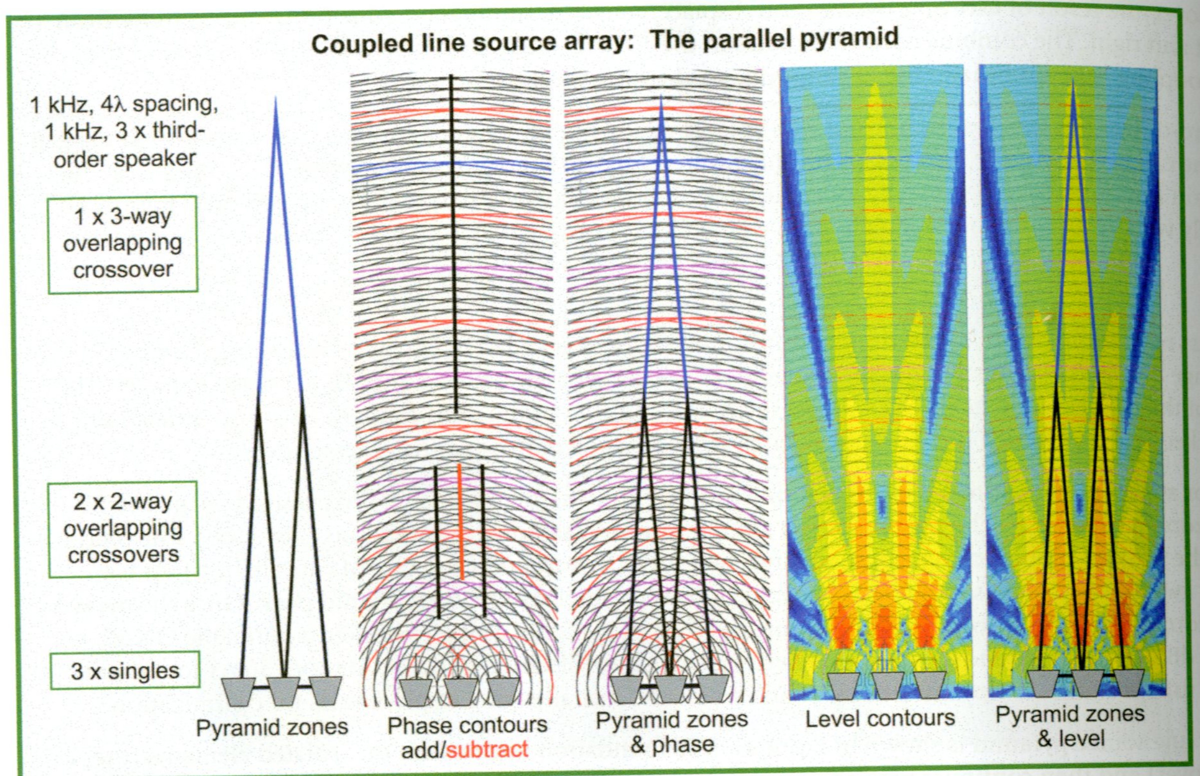


FIGURE 4.40
Parallel pyramid for three elements

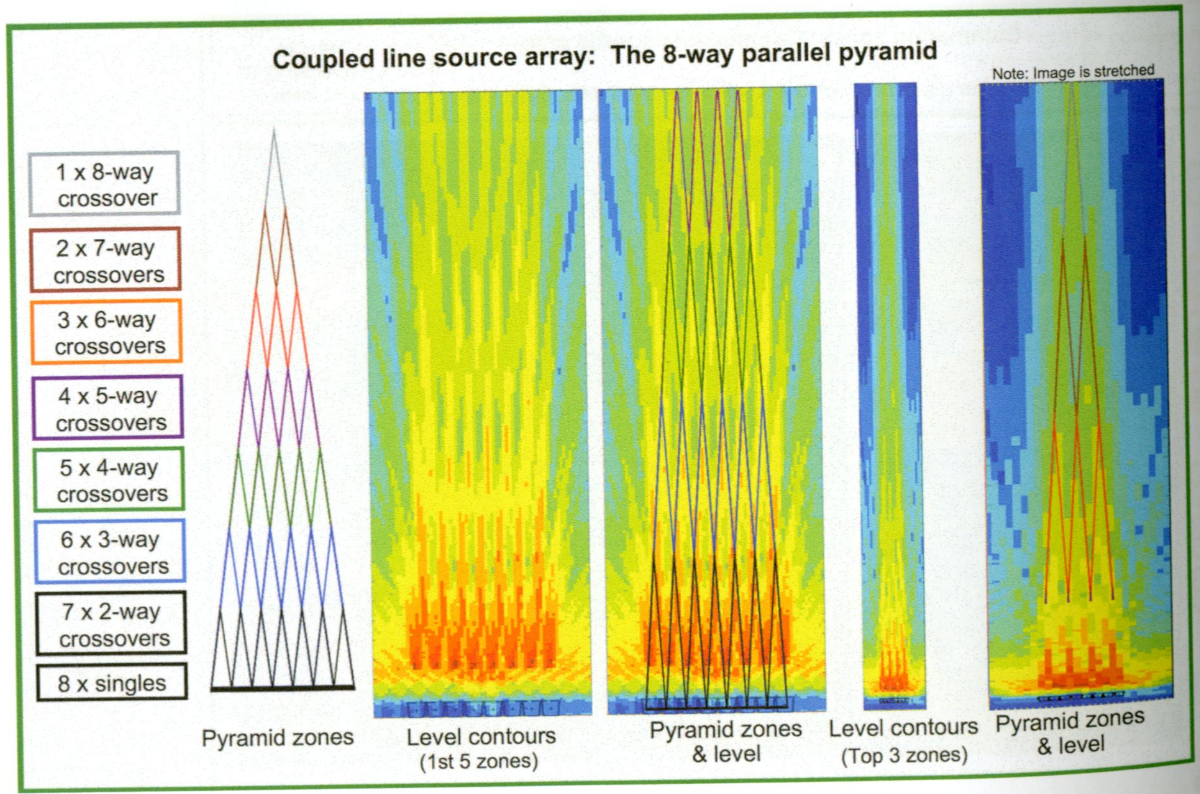


FIGURE 4.41
Parallel pyramid for eight elements

crossover) is controlled by the same factors discussed earlier: element coverage angle and displacement. The distance to each successive step is the same, so the total height is found by multiplying the step height by one less than the element total (e.g. an eight-element pyramid height = distance to first crossover × 7). As elements become more directional or displacement increases, the step height multiplier extends. Because directionality is variable over frequency, the pyramid step height will vary over frequency, which when multiplied can create vast differences in combined shape over frequency.

Combining wide speakers yields less width. Combining narrow speakers yields more narrowing. The more the narrower. If the element starts with wide LF and narrow HF, the array response will end up the same way (relatively to each other). The combination will be proportionally narrower than the single element at every frequency. The coupled line source is an equal opportunity squeezer.

Summation zones

If we hold to the definition of "coupled line source" we have a one-step summation zone progression: coupling. The crossover area (the coupling line) gets the maximum and the sides (non-coupling line) get the minimum. It's all good until somebody gets out of line. I mean out of phase. Real loudspeakers take up space(s). Keeping the phase offset under 120° becomes increasingly challenging as frequency rises. Because there's no road to angular isolation, displacements over 120° push us into the combing zone. It's a race. If we finish the coverage before combing begins we win (i.e. we reach -6 dB off axis before the phase offset is >120°). Let's start with two elements spaced 1 ms apart. Start with F = 33 Hz (T = 30 ms). The phase offset is 1/30 λ (12°). We win. Next: F = 333 Hz (T = 3 ms). The phase offset is 1/3 λ (120°). It's a tie. Things don't look good for 3333 Hz do they? We can't beat the phase offset, which maxes out at 1200°. How about level? Bear in mind that our maximum phase offset (1200°) is along the non-coupling line, which is 90° off axis from crossover. If our speaker has less than 180° of coverage it won't make it to the 90° finish line with enough level to win. The critical location is the radial angle that corresponds to 120° phase offset. The answer for 3333 Hz is ±10° as shown back on Fig. 4.21. A displacement of 3 λ creates 120° phase offset at the radial 10° mark (relative to center between the elements). Raise the frequency an octave and we have only ±5° to work with. The same thing happens if we double the displacement. We've established a sliding scale. For a given displacement we can neutralize the combing zone damage by proportional reduction of the coverage pattern. We maintain our position if we halve the coverage as we double the frequency. It should be obvious that the advantage in combing suppression is balanced by a serious side effect: radically different coverage over frequency. But this is the fate of the coupled line source if it plays with wavelengths too hot to handle. If we keep it on the down low, in the heart of the coupling zone, we can leave coverage out of the equation. But if we keep wide coverage all the way to the top end in a coupled line source we will pay the price.

Coupled line source conclusions

- Coupling frequency limit is set by element displacement ($F^{LIM} = 0.33 \times T$) where T is the displacement in ms. For a 3 ms displacement (about 1 m), $F^{LIM} = (0.33 \times 0.003)$. F^{LIM} = 110 Hz.
- Audible combing effects can be reduced if the coverage pattern narrows as phase offset rises (due to displacement). The maximum comb-free coverage angle = 60°/λ displacement. Example: Two sources 4 λ apart have a maximum coverage angle of 15° (60°/4).
- This array type works for subwoofers but has severe limitations above that range.

We already have a conclusion that eliminates first- and second-order speakers from contention in the coupled line source, but the massive combing we saw in Figure 4.37 should help to alleviate any doubts. First-order elements (≥60° wide) cannot exceed 1 λ displacement. Second-order speakers range down to 20° wide, which corresponds to 3 λ. That's 0.17 ms at 18 kHz (as long as these six words). These elements must be very closely spaced small speakers. This leaves us with proportional beamwidth third-order speakers with their ever-narrowing coverage pattern as frequency rises. There are no rooms that get narrower as frequency rises so this will not provide uniform coverage over frequency. The third-order proportional beamwidth element does have two things going for it: lots of coupling (power gain) and the highest tolerance to overlap. We'll soon put it to use by adding some splay.

4.4.2.2 COUPLED POINT SOURCE

The coupled point source approaches arrays from an entirely different angle (one that's not 0°). Adding splay angle to the equation enables an isolation mechanism that opens up many possibilities for variable array shapes. We can mix speaker orders, splay angles and levels for shaping. The coupled point source has one feature no other array type can duplicate: maintaining a unity class crossover over extended distance. It's not automatic, and is variable over frequency, but no other array can duplicate this for even a single frequency. The coupled point source is the steady long-distance runner. If the coverage angle remains constant over frequency, so will the unity class crossover. That's what we call uniformity of coverage. The gap, unity and overlap areas are all angularly defined and maintain their character over distance.

Let's begin with a first-order pair (90°) at unity splay (Fig. 4.42). The summation zone progression originates at XOVR (coupling zone) and reaches isolation after a brief stay in the combing zone. The progression maintains its angular qualities over distance. Isolation zone behavior is visible in the HF response. The displacement is small enough to limit the MF disturbance to a single -9 dB null before breaking into isolation. The small displacement keeps the LF range entirely in the coupling zone. Note the overall resemblance of the HF, MF and LF shapes, indicative of a similar frequency response across the 180° coverage arc.

Next is a second-order (40°) pair at unity splay (Fig. 4.43). The zone progression is more angularly compressed than the first-order pair. Isolation arrives more quickly due to the steeper spatial filter slope of the second-order speaker. The 40° splay angle results in 0% overlap (unity) @10 kHz, creating a combined shape of 80°. Coverage is highly overlapped at 1 kHz (100° elements at 40° splay), creating more combing and a much wider combined coverage angle of around 140°. The LF response is similar to the first-order scenario.

Next is a third-order proportional beamwidth element with an HF unity splay of 8° (Fig. 4.44). A notable feature of this highly directional element is the visible gap in the near-field HF response. Farther away the crossover has reached unity, which will hold out for an extended range. Recall that the third-order system has the highest LF/MF/HF coverage angle differential, which reduces the unity splay range to a small minority of the spectrum. The overlap percentage exceeds

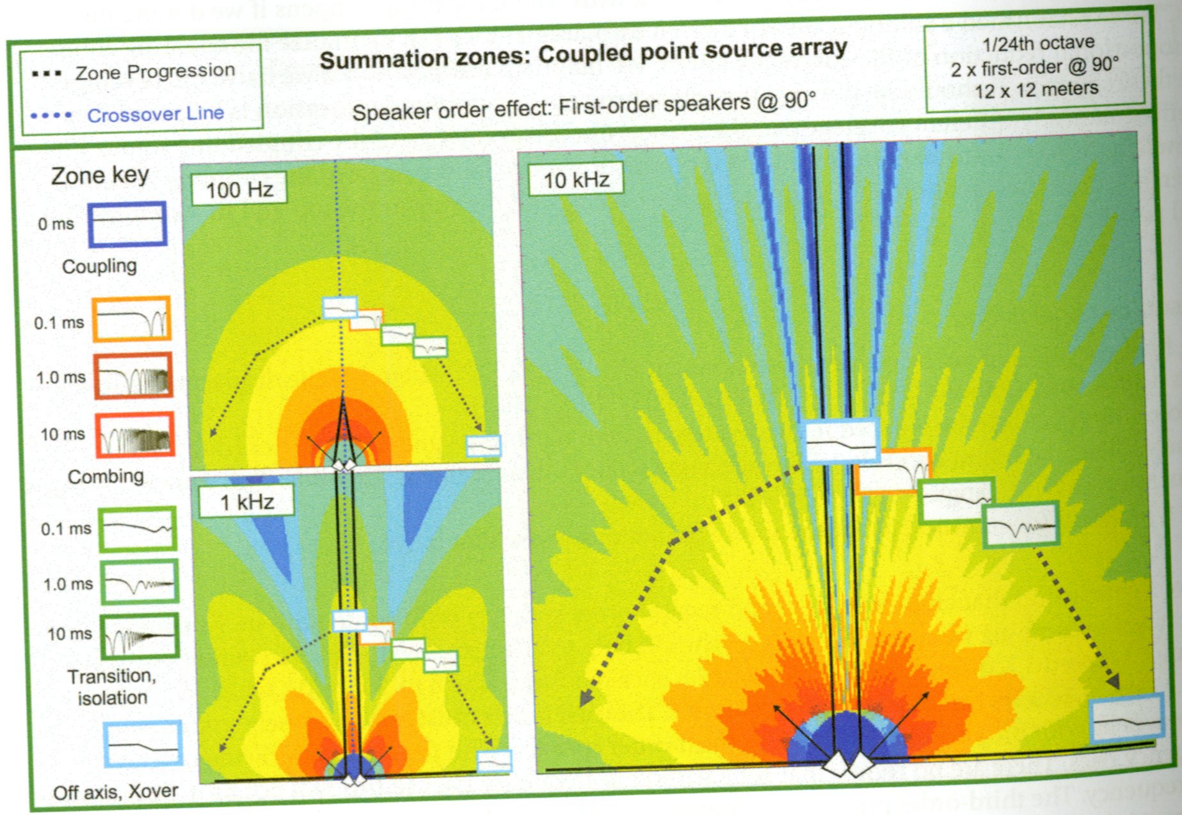


FIGURE 4.42
Summation zone progression factors for the coupled point source array, first-order

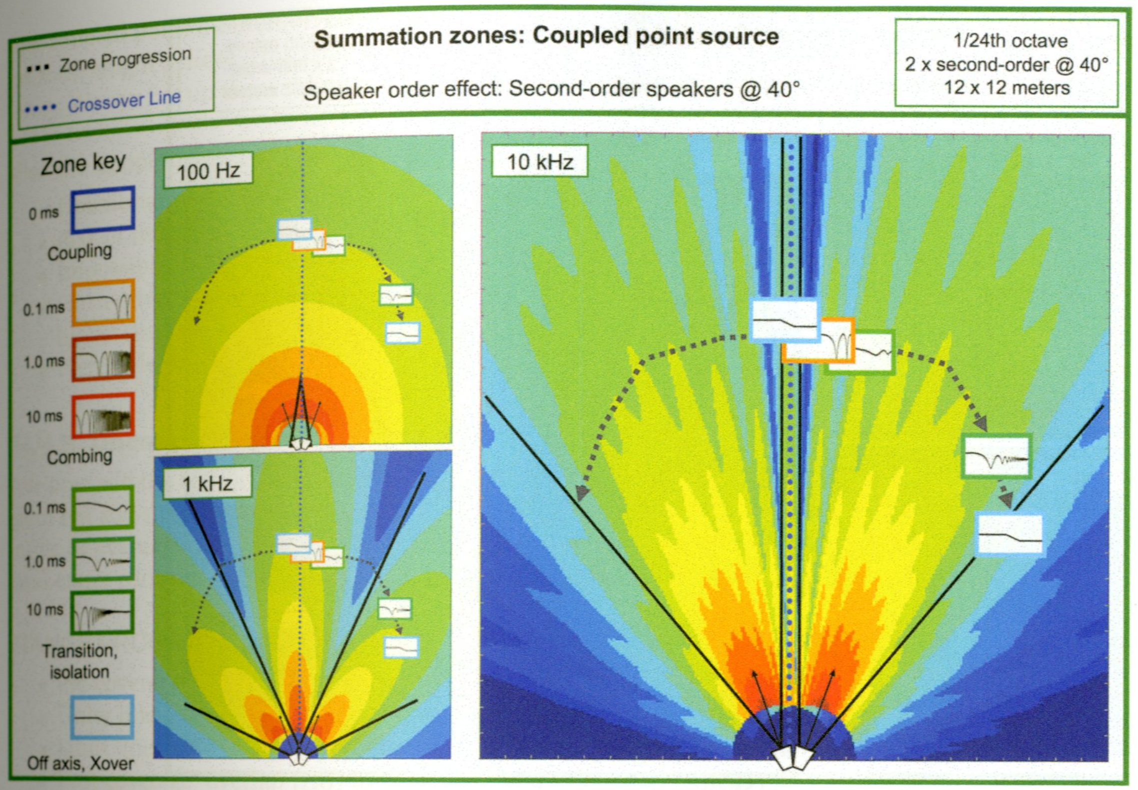


FIGURE 4.43
Summation zone progression factors for the coupled point source array, second-order

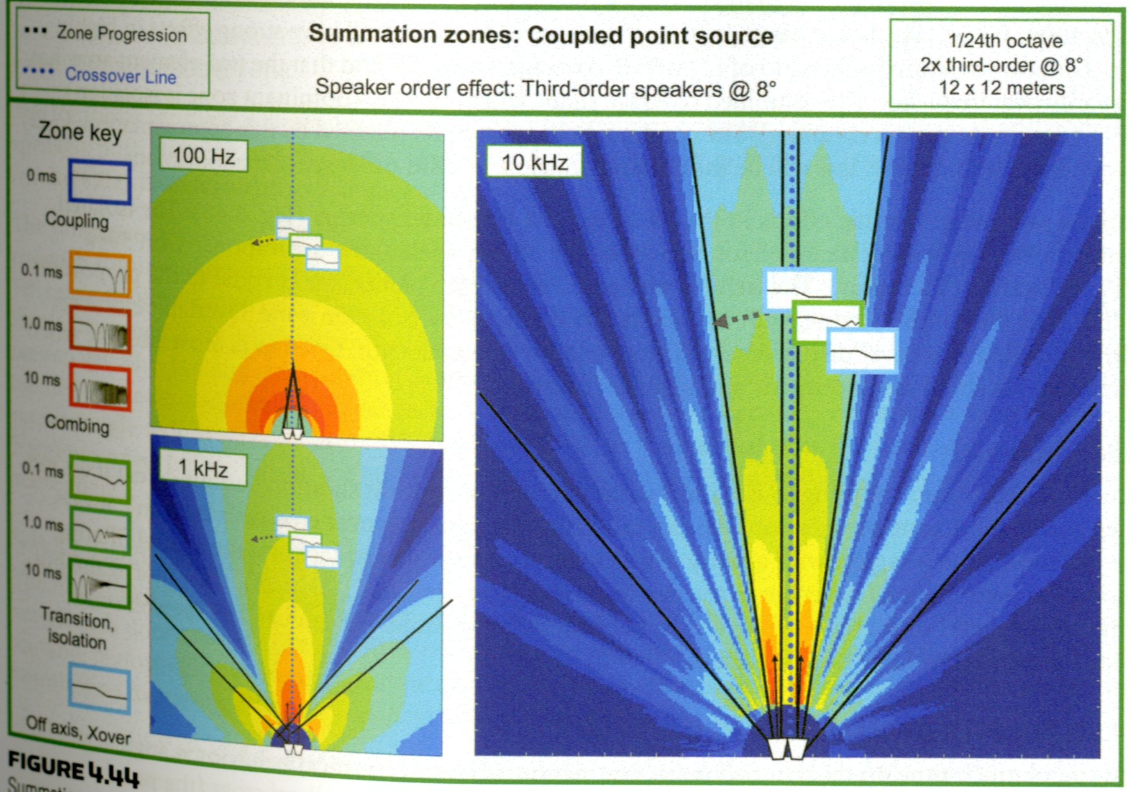


FIGURE 4.44
Summation zone progression factors for the coupled point source array, third-order

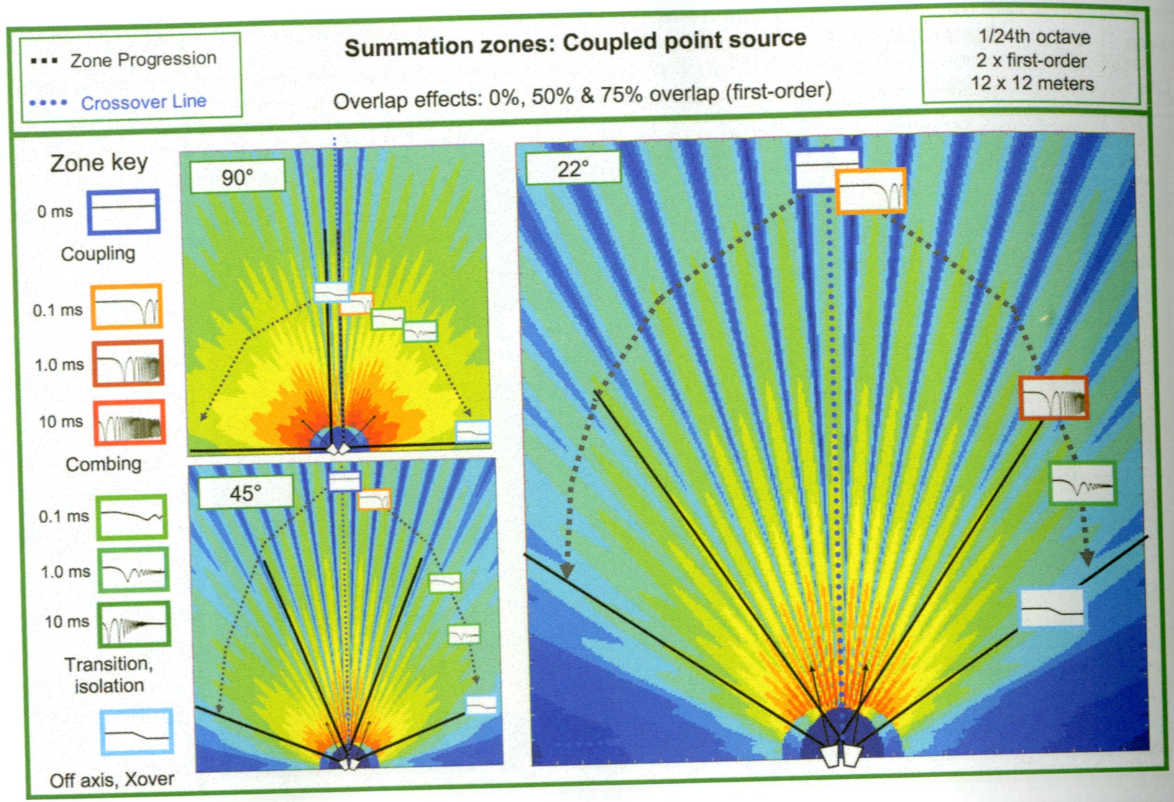


FIGURE 4.45
Summation zone progression factors for the coupled point source array, overlap effects

90% @1 kHz, resulting in a null depth greater than 20 dB. The presence of midrange combing does not eliminate this array from consideration. We will see, later, that an increased quantity of elements will have strong effects in highly overlapped arrays. For now we return to the ratio of LF/MF/HF coverage, where we find that the two-element array has decreased the disparity over frequency. The combined coverage shape widens the HF (dominant zone is isolation) and narrows the LF (dominant zone is coupling). The combined ratio can be represented by this approximation: ½ LF/MF/2 × HF. As we will see in Chapter 9, this will be the guiding principle in third-order speaker applications.

We now focus on the percentage overlap effects in the HF range of a first-order speaker (Fig. 4.45). The isolated (0% overlap) version from Fig. 4.42 is included for reference. The other panels show the response with 50% (45° splay) and 75% overlap (22° splay). The trend is obvious: The overlap percentage is equal to the proportion of the coverage that is in the combing zone, with the remainder being in the isolation zone. Overlap percentage must be carefully controlled whenever displacement is large relative to wavelength. Overlap is most effective when coupling is maintained via small displacements and angular control.

Summation zone progression

It's possible to make the run from coupling to isolation without combing, but we shouldn't admit defeat if we run the full seven-step summation zone progression. We can minimize the combing near crossover but can't always eliminate it. The isolation zone is largest with a unity splay crossover. As speaker order rises, the spatial filtering steepens, increasing the percentage of coverage in the desired zones (coupling and isolation). It's a race again, but angular isolation provides level offset relief when we get in phase offset trouble. We can use any speaker order, choosing to divide the pizza into large or small slices.

4.4.2.3 COUPLED POINT DESTINATION

We don't need to spend much time on the coupled point destination array. Its acoustical behavior is angularly similar to the point source, but with a forward focal point. The location where the speakers cross (the point destination) becomes the substitute point source. It's the same principle as a concave mirror. The chief deficiencies of the coupled point destination are mechanical and practical. There isn't a vortex disturbance in front of the speakers as some might believe. This array is selected only under duress, like an I-beam is blocking the horn of a point source array. We can fire up the welding torch or invert things and make it a point destination that can reach the audience.

For the coupled point destination array

- Functionally equivalent to the coupled point source (splay angle, frequency, etc.).
- Risk of reflecting off neighboring elements rises with quantity and overall splay.
- Impossible to array beyond 90° because elements are aimed through other elements.
- Horn driver placement at the cabinet rear creates unfavorable geometry. Point destination arrays usually have higher displacement than their comparably angled point source counterpart.
- Preferable only when physical logistics win over the point source counterpart.

4.4.3 Uncoupled arrays

We now add the second isolation mechanism: spacing the speakers apart, i.e. uncoupling. We pay a price in power gain but add shaping capabilities not present in the coupled arrays: lateral and forward extension. Uncoupled arrays must be evaluated in progressive stages over distance. The elements begin as clear soloists and then make duos, trios and entire choruses. As we'll see, sweet harmony often ends at the trio and gets worse from there.

RANGE PROGRESSIONS FOR AN EXTENDED SERIES OF UNCOUPLED ELEMENTS

- Pre-coverage: isolation (A) to gap (XAB) to isolation (B) and onward.
- Unity line: isolation (A) to unity (XAB) to isolation (B) and onward.
- Limit line: isolation (A) to overlap (AB) to overlap (ABC) to overlap (BCD) and onward.
- Post-coverage: overlap (AB) to overlap (ABC) to overlap (ABCD) and onward.

The pre-coverage range is used for fill speakers in singular areas. The unity line maintains consistent coverage by the principle of the unity class crossover. The limit line indicates where multiple paths with differing time offsets give the combing zone the majority. The most uniform coverage area lies between the unity and limit lines. In practice we design uncoupled systems to transition coverage to others at the limit line. Beyond the limit line are the tall weeds of the combing zone.

The locations for these milestones are influenced by element coverage (speaker order), spacing and splay. Narrow speakers push the start points deeper, as does wider spacing and outward splay. Wide speakers, closer spacing and inward splay hasten the progression.

The range progressions show a clear favoritism for speaker order. There's advantage to having all frequencies progress through the zones together. We don't want the LF and MF ranges to be in post-coverage combing when the HF range finally hits the unity line. The ideal uncoupled array element would have a flat beamwidth over the entire frequency range. This is unrealistic but we can dream, eh? In practical terms, we seek the longest beamwidth plateau we can get. This is standard operating procedure for first-order speakers. They are, by far, the favored uncoupled element, in large and small formats. Second-order speakers have a greater challenge. A long beamwidth plateau at a narrow angle requires a large horn. We might see these as festival frontfills that have several meters of open security barrier to travel before hitting the audience. Don't expect to see them at *Wicked*. Third-order speakers are a non-starter here.

4.4.3.1 UNCOUPLED LINE SOURCE

The uncoupled line source differs from its coupled cousin in scale only. That's not a small detail, however, because wavelength doesn't scale. The coupling of the parallel pyramid will be restricted to the LF range. Expect highly variable performance above that. An uncoupled array has a continuum of behavior, with tendencies toward coupling as frequency falls and isolation and combing as frequency rises.

We begin with a set of five first-order elements with 3 m spacing (Fig. 4.46). Notice that the response has repeating horizontal themes but is drastically different over depth, a standard feature of all uncoupled arrays. This contrasts with the coupled point source array, which held its angular shape over distance. The gap zone is visible in the

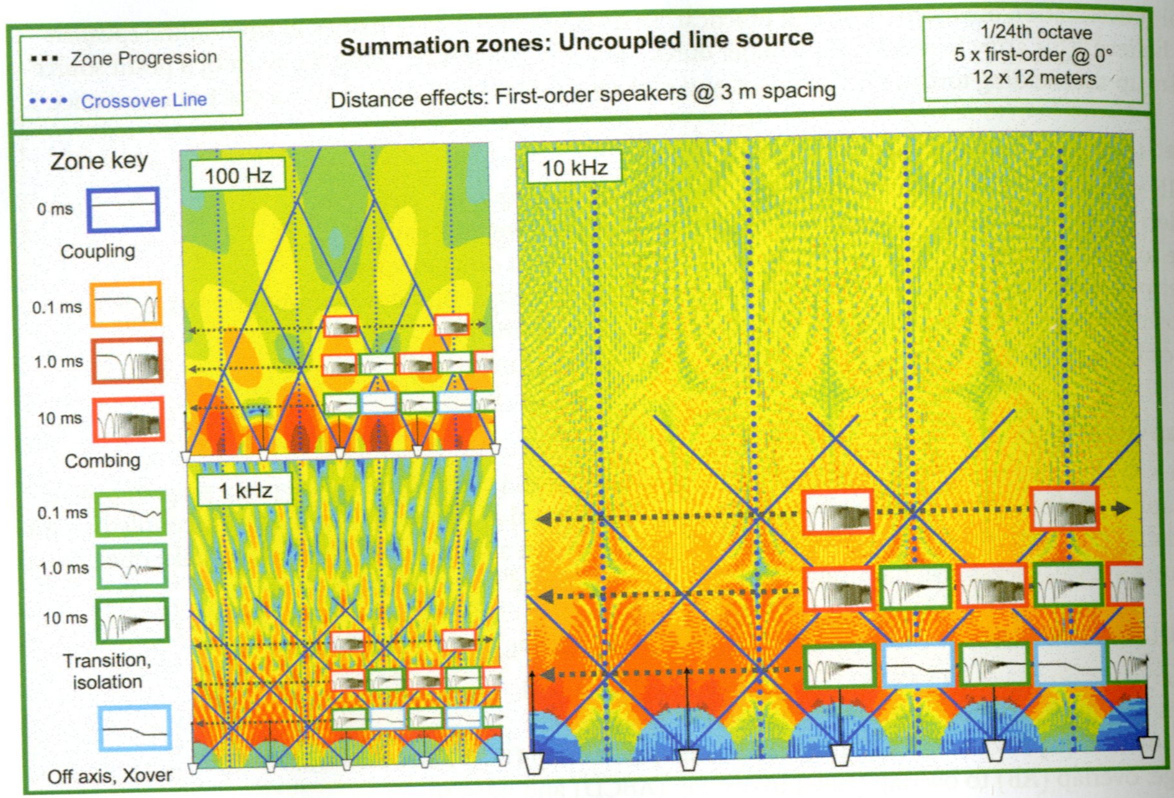


FIGURE 4.46
Summation zone progression factors for the uncoupled line source array, first-order speaker

near-field HF response. The first summation zone progression is the unity class crossover line, which alternates between isolation at ONAX and coupling at XOVR, with transitions into combing between. Positions along this line enjoy the highest uniformity and immunity from ripple. We lose the isolation zone as we move deeper into the shared coverage of two or more (or more again) speakers. The multiple paths created a cascade of combing zone summations. Recall the multiple levels of the parallel pyramid. They are back, but in this case they decimate the response with combing rather than concentrate it with coupling. The weave becomes increasingly dense as we go deeper, with peaks and dips that vary with frequency and location. Maximum uniformity over the width is found in the range between the unity crossover line and the limit line (the depth where three elements converge). Combing becomes increasingly dominant beyond the limit line, which means we need another system to take over the coverage. The relationship between the unity line and limit line is simple for the line source (assuming matched elements and spacing): The limit line is double the distance of the unity line. If we close the gap in 2 m (unity line) then we want to end the party at 4 m (the limit line). Let's turn to the LF response where we can see the parallel pyramid, evidence that our spacing is close enough to maintain coupled line source behavior in this range.

Let's change to a second-order element, which extends the distance to the unity line and enlarges the gap area, but only for the HF range (Fig. 4.47). The MF response (and the MF unity line) is the same as previously, which means our zone transitions are now progressing at different depths. The MF range is already overlapped before the HF has closed the gap. The easiest way to keep the unity line consistent over frequency is to build it with elements that are consistent over frequency (i.e. a flat beamwidth over a wide range). This carries through for all of the uncoupled array configurations.

Round three features a horn-loaded second-order system with increased HF and MF directional control (Fig. 4.48). This extends the crossover progressions in both the HF and MF regions at nearly the same rate. The uniform coverage area (between the unity and limit lines) starts later and has greater depth extension than the first-order system even though the displacement is the same.

First-order elements with an extended beamwidth plateau are well suited for uncoupled line source applications. Second-order systems can also work well provided their directional control extends below the HF range. Third-order elements are unsuitable because of their inconsistent shape.

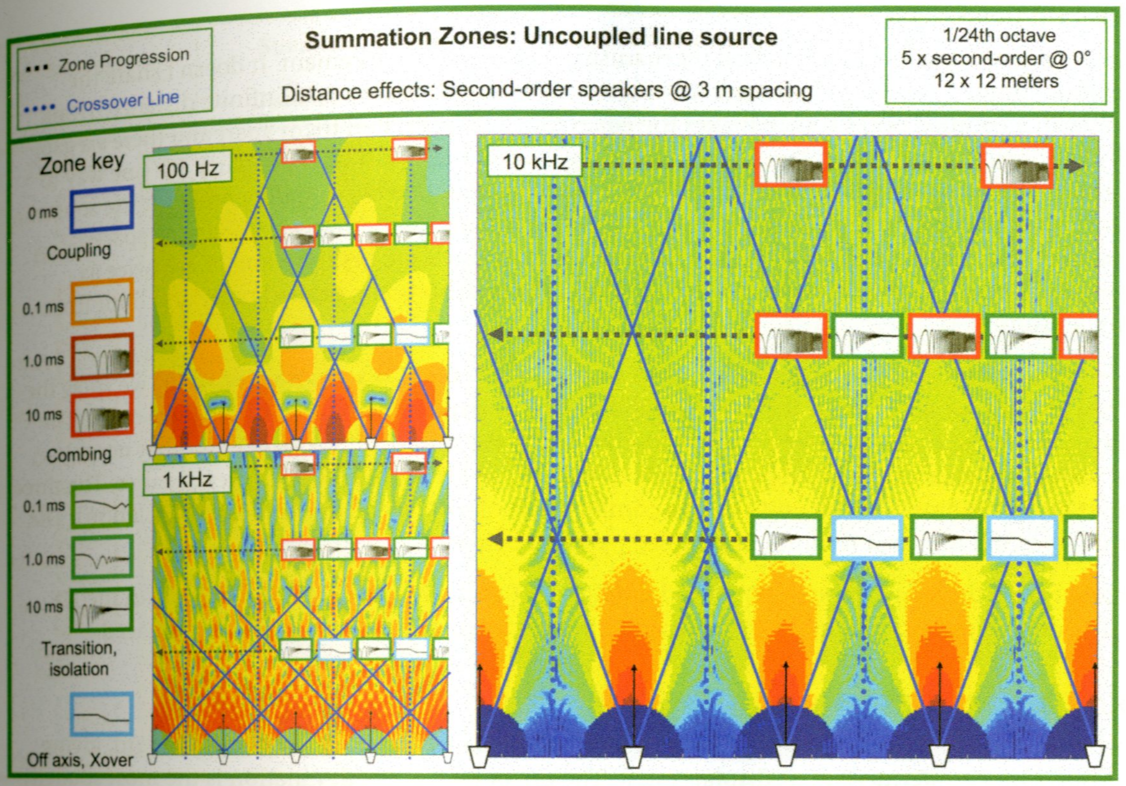


FIGURE 4.47
Summation zone progression factors for the uncoupled line source array, second-order speaker

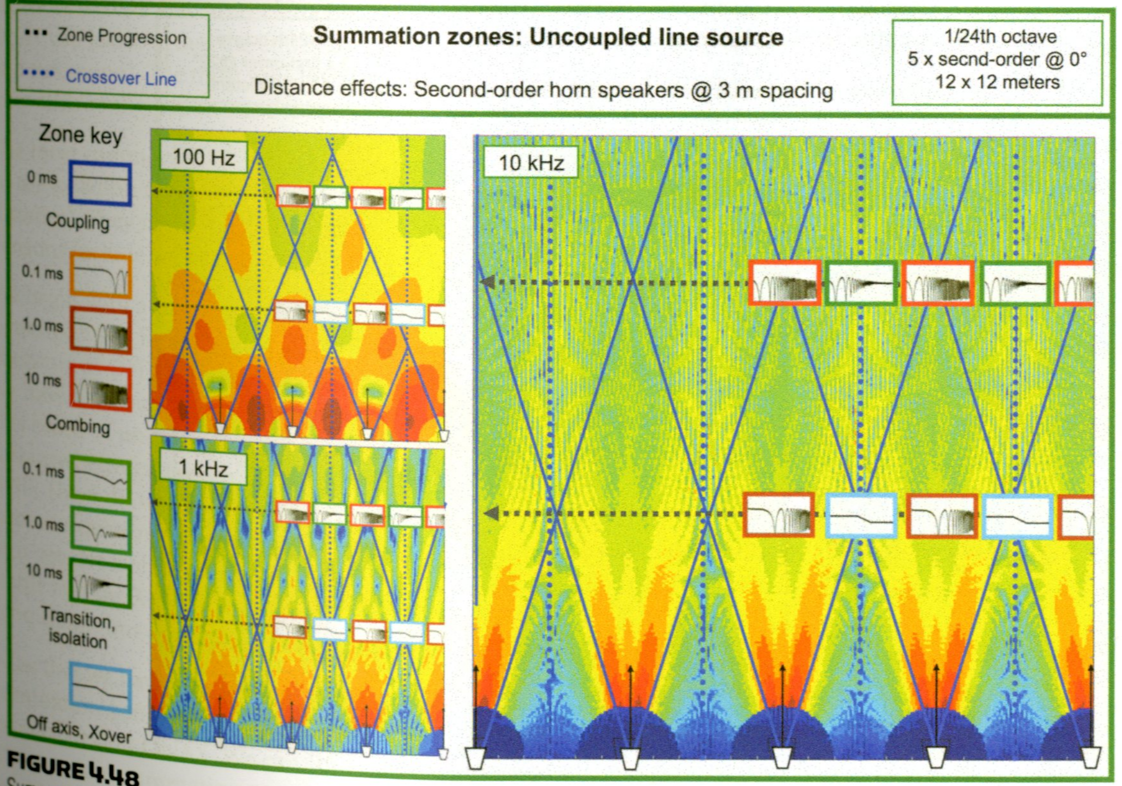


FIGURE 4.48
Summation zone progression factors for the uncoupled line source array, second-order horn-loaded speaker

4.4.3.2 UNCOUPLED POINT SOURCE

The uncoupled point source utilizes both isolation mechanisms: angle and displacement. It doesn't share the foremost feature of its coupled counterpart. It can't maintain a unity class crossover over infinite distance. Think about it. Unity splay in a coupled point source makes the edges touch, forever. Pull them apart and there's a gap, forever. A 3 m displacement and a unity splay angle means they'll never meet (always 3 m apart). It's one way to handle a center aisle! If we want unity somewhere we'll need some angular overlap to compensate for the source displacement. Once the gap is closed, this array will have a greater working depth than a comparably spaced uncoupled line source, because it takes longer for the third element to reach the first (the angles are twice as far apart). The design process includes strategic placement and splay to achieve the desired unity and limit line positions (covered in section 11.5).

We begin again with first-order speakers and resume our 3 m spacing. In the first scenario (Fig. 4.49) we splay the elements with 75% overlap, which extends the gaps and the unity line depth beyond that of the line source. The central area is the most affected because it becomes triple-covered by the middle of the panel. Another notable effect here is the correspondence of the LF response shape to that of the MF and HF shapes over distance. The three ranges have similar overall contours at the unity line (a combination of displacement and angular isolation). The LF response narrows beyond that as it resumes its coupled pyramid behavior.

The second scenario opens the splay angle to 50% overlap (Fig. 4.50). A large isolation zone dominates the HF response panel. The outer elements will never meet because they are angularly isolated and 6 m displaced.

4.4.3.3 UNCOUPLED POINT DESTINATION

The isolation roads are angle and displacement. The uncoupled point destination turns the angle inward, giving us "reverse isolation." Our countermeasure is displacement. The uncoupled point destination is the most spatially variable array type and yet a necessary tool for us. Variability rises as we turn the angles inward, reducing our usable coverage range.

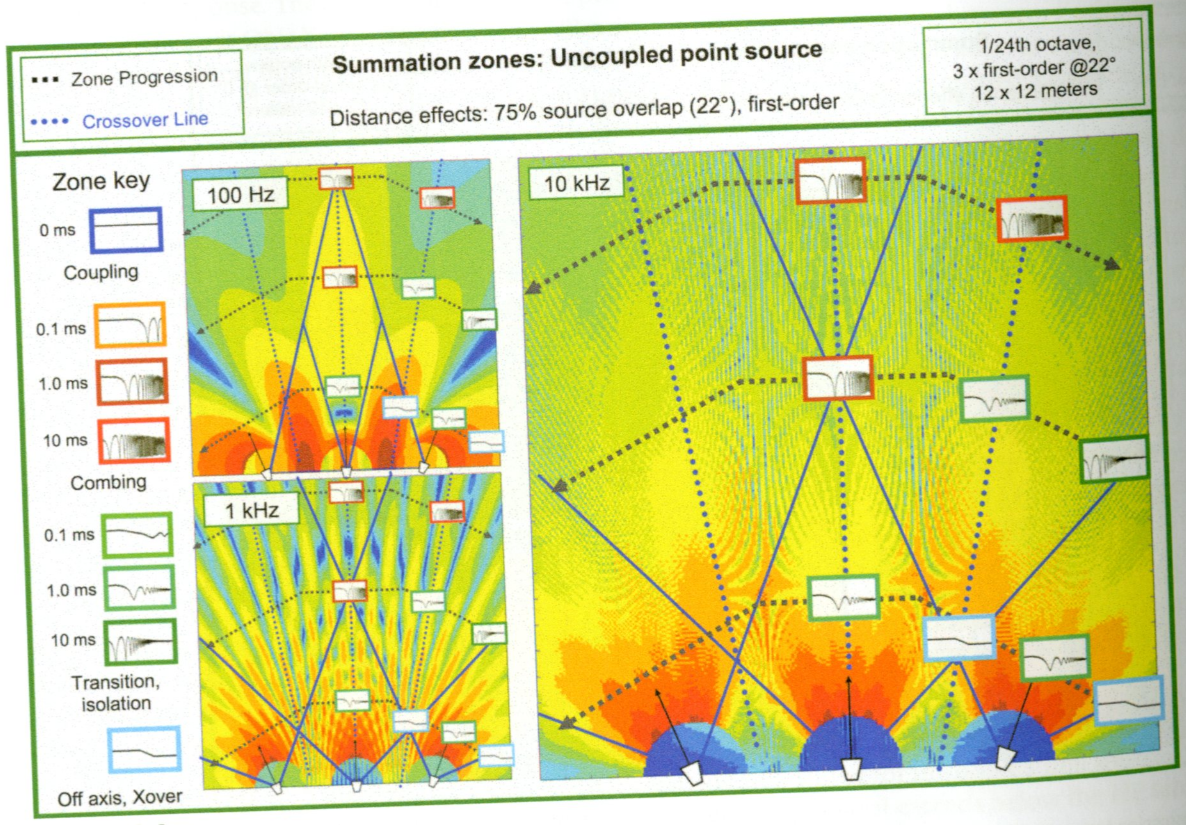


FIGURE 4.49
Summation zone progression factors for the uncoupled point source array, first-order, 75% overlap

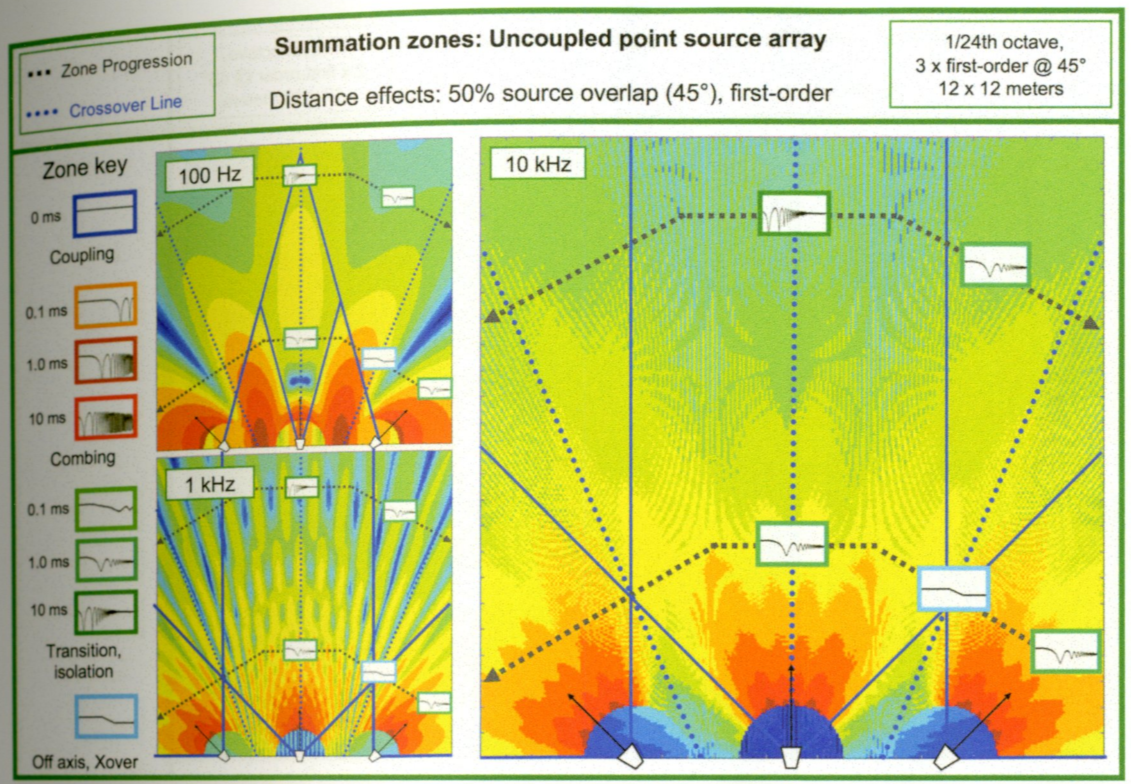


FIGURE 4.50
Summation zone progression factors for the uncoupled point source array, 50% overlap

A symmetric uncoupled point destination has its most uniform response in the isolated pre-coverage area, where speakers are more soloists than array elements. Infill speakers are like this. Each covers its side and we hold our nose at center. Don't you just love that the critics always sit there? Another symmetric version is left and right mains (if turned inward and run mono). The most well-loved symmetric form is the monitor sidefill. Will it make you feel better, or worse, to know this configuration has the statistically highest possible spatial variance? There *is* a worst-case scenario and this is it.

The most common asymmetric version is the main + delay speaker combination. The coverage patterns overlap so the isolation mechanism turns out to be asymmetric level (the delays drop off quickly due to their short doubling distance). They meet at crossover but can continue to be close in level only for a limited range. Other asymmetric versions include various arrays of arrays (e.g. joining the mains to the frontfills in the third row).

We begin with a first-order pair facing 45° inward (Fig. 4.51). The unity crossover (XOVR) is found where the pattern centers intersect (the destination), but this must be a different kind of unity. The other arrays have coupled coupling of OFFAX edges together to build a unity crossover to match the isolated ONAX locations. In this array we have our coupling zone *at* the on-axis center line and the isolation zone seems to have disappeared. What is this breed of unity crossover referenced to? Unity compared to where? The unity location (ONAX) is found half the distance between the speakers and XOVR. Why? We return to the inverse square law: Double the distance and lose 6 dB. The 6 dB we lose between the mid-point (ONAX) and the crossover (XOVR) will be returned to us in coupling zone summation. The mid-point location should be dominated in level by the local speaker, so this will be as good as it gets for isolation zone response. Some familiar behaviors are present: The isolated area (ONAX) is the most stable and the XOVR area the least. Movement between XOVR and ONAX changes the distances between the sources (combing), but does not necessarily give us isolation by angle (we may still be in the coverage of both speakers).

Now that we have two reference points on our map, we can begin to analyze the spatial qualities of this array. The summation zones progress in multiple directions outward from the crossover point. Our area of principal concern centers around ONAX. We can find angularly related off-axis points from here that will define the coverage edges. The standard summation progression holds when traveling between ONAX and XOVR, albeit highly combed. The land beyond XOVR is wild country dominated by combing.

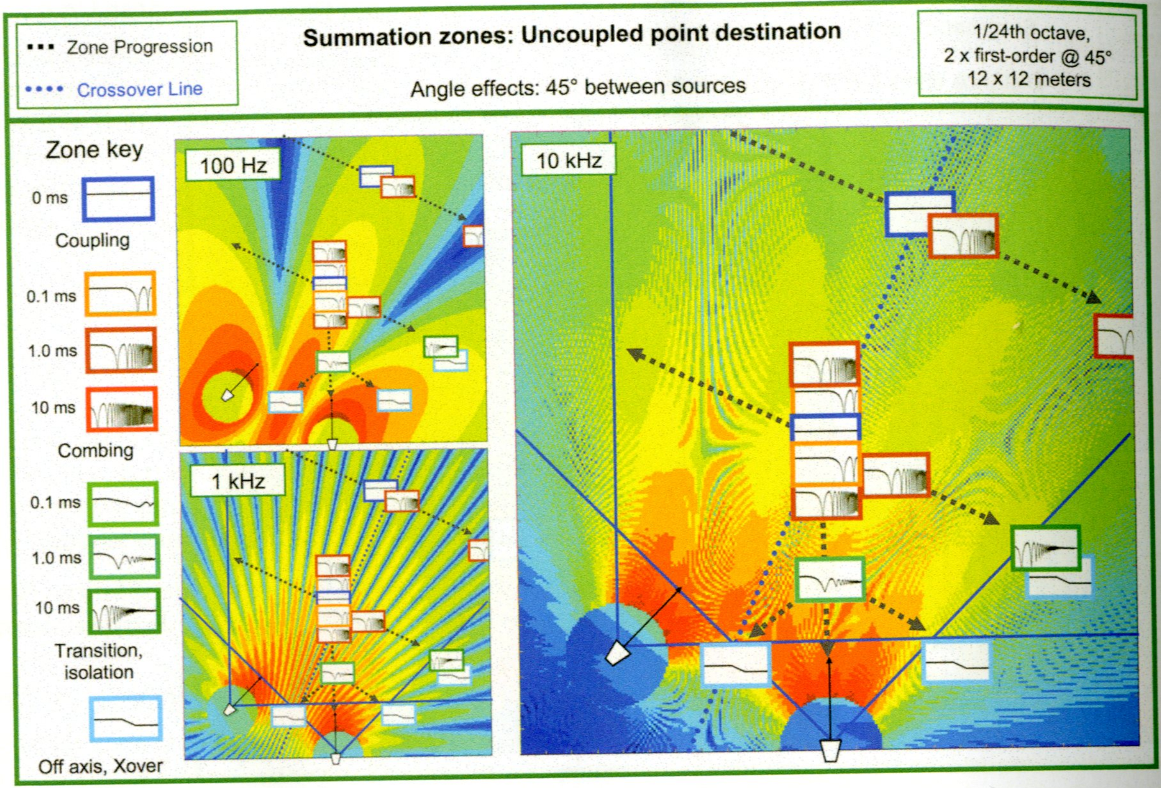


FIGURE 4.51
Summation zone progression factors for the uncoupled point destination array, 45° angle effects

We can increase the inward splay angle to 90° (Fig. 4.52). As we approach one speaker we are moving perpendicular to the other. Our reference points are the same: mid-point (isolated) and crossover (coupling). The angular change has a muted effect between our two reference points but has a very pronounced effect on the surrounding areas. As the angle rises, the rate of response change in the peripheral areas increases proportionally. Additionally the proportion of areas with redundant and highly displaced MF and HF coverage rises, creating worst-case scenario combing.

Combing becomes even more widespread with a 135° inward angle (Fig. 4.53) and finally we reach the most inward angle of all: 180°. This array has the dubious distinction of having the most rapid movement into the combing zone and the least prospect of escape. If we are within the coverage of one element, we are within the coverage of the other. It's guaranteed. The rate of change is the highest because a movement toward one element is *de facto* a movement away from the other.

We move on to the asymmetric version of this array. A common application is the delay speaker combined with the mains (Figure 4.54). The speakers are displaced, yet have the same angular orientation, so "on axis" is the same line for both. The delayed speaker is turned down in level, which gives us a range for unity combination. This ONAX reference is forward of the delay, and depends on exactly where we want it to be for the application. We set the level so that the patrons in the delay area (XOVR) have matched combined level to those in the middle of the hall (isolated mains coverage). Time offsets begin to accrue and combing zone interaction takes its toll as we move away from XOVR. Level asymmetry limits the range of combing zone interaction as we depart the crossover area because the main speaker retains level dominance over most areas, due to its longer doubling distance. The combing is inevitable in any case, but, like its symmetric counterpart, rate of change is highly influenced by the angular relationship between the sources. Fig. 4.54 shows the relationship of angle to rate of change for this array. The proportion of combing zone interaction rises as angle increases.