Installed Sound
Technical Guide

Control of Lower-Midrange Directivity in Sound Reinforcement Loudspeakers Using Crossover Overlap Techniques

TA-7
Version 1.0
April, 2002

Summary

Sound reinforcement and concert loudspeaker systems must satisfy many performance criteria in order to provide not only high fidelity reproduction, but also a high degree of intelligibility. Control of directivity and coverage is an integral and important part of the design of these systems in attaining their performance goals. This paper describes a technique to increase the lower-midrange directivity and decrease the vertical beamwidth of large sound reinforcement speaker systems through crossover overlap. Rather than operate the individual low-, mid-, and high-range sections of the speaker independently in their own frequency bands, the new technique overlaps the operating frequency ranges of the low- and mid-range sections. This overlap increases the effective vertical source height of the system, thus decreasing vertical coverage, and raising directivity in the upper bass and lower midrange. Proper implementation of the overlap requires an electronic crossover/processor with all-pass filter capability that allows manipulation of phase independent of signal magnitude.

Introduction

Concert and sound reinforcement speaker systems must satisfy many performance goals including high-fidelity reproduction, high intelligibility, being able to play loud and clean, providing even coverage of the audience area, and high reliability. Of all these performance goals, one of the most important is the coverage pattern of the loudspeaker. Ideally the system should provide good even coverage of the audience area, but with minimal coverage of other areas such as reflecting surfaces where the listeners are not located. Coverage of the audience only and not other areas, is very important in reverberant environments to maximize intelligibility and to extend the operating reach of a system.

Typically, concert speaker arrays are made up of individual multi-way full-range systems, rather than individual clusters of like-frequency-range components such as high-frequency horns or midrange horns. When these full-range systems are used in smaller arrays or individually, it is very important that the individual systems provide high directivity on its own and not depend on the additive coverage of adjacent units. Often, the multi-way full-range systems are composed of relatively small individual sections that cannot provide proper coverage on their own. This is particularly true for the midrange horn where its limited size precludes it from having sufficient directivity and vertical coverage control at the low end of its operating range.

A method of overlapping the frequency ranges of the woofer and midrange sections of a three-way system, is described here, that significantly raises upper bass and lower midrange directivity and decreases vertical beamwidth. This directivity increase much improves the lower midrange punch and intelligibility of the system in reverberant and semi-reverberant environments. Increasing or maintaining a higher level of directionality over a wider bandwidth will raise the ratio of direct-to-reflected energy in a reverberant environment, thereby increasing system intelligibility.

Coverage Control

It is quite simple to produce a device that is very directional over a limited frequency range. A horn's ability to control, or direct, a radiated pattern is one of the principle reasons horns still enjoy such widespread use. Unfortunately, any acoustical device begins loosing its ability to control its radiated energy when the radiated wavelengths become long compared to the dimensions of the device. For horns, this occurs when the wavelengths become long compared to the height or width of the horn mouth. Unfortunately, horn mouth size grows even larger for a given lower frequency limit, when the desired directivity is raised (higher Q).

As an example, a horn-loaded speaker system is desired that will produce a uniform symmetrical pattern of 100° down to 200 Hz. The required horn mouth size would be approximately 1.25 x 1.25 m (4.1 x 4.1 ft) for this situation [1]. The resultant directional pattern would actually represent a very well controlled system. This is in contrast to a typical two-way sound reinforcement system consisting of a non horn-loaded 15" woofer and a relatively small high-frequency horn, which radiates essentially omni-directional up to 200 Hz. For an even narrower pattern of 60° down to 200 Hz, the horn's size would need to be a much larger 2.1 x 2.1 m (6.9 x 6.9 ft.)!

Because human male vocal fundamentals extend below 100 Hz, it is very important for maximum intelligibility that pattern control extend to below this frequency. Two effects occur in sound reinforcement systems to reduce vocal recognition. First, low directivity control in the lower vocal range will produce a very poor ratio of direct-to-reflective energy. The higher the direct energy with respect to reflected energy, the higher the intelligibility. Secondly, in a live situation, poor directional control at lower frequencies will allow signals from the sound reinforcement system to reenter the live microphone directly from the PA system (with, of course, a delay associated with the spacing from the PA system to the open microphone). The delayed signal will combine with the direct vocal signal and will be re-radiated into the reverberant environment further compounding an already difficult situation. This same energy can also produce feedback in the lower vocal range.

Current Practice

The current practice in performing arts centers, houses of worship, and live entertainment venues is to use medium-format three-way horn-loaded systems. These high-performance systems offer excellent output capability, low distortion, and very linear response. Unfortunately, the coverage pattern of a typical individual system of this type is much too broad below 500 Hz, which results in speech intelligibility problems in reverberant environments. Typically, the radiation pattern is already 100° horizontal by 100° vertical at 500 Hz. As frequency goes down and wavelengths increase, the pattern widens even more. For a typical system with a horn-loaded mid bass with mouth dimensions of 0 5 x 0.5 m (20 x 20 in.), the pattern is even wider at 200 Hz increasing to 250° by 250°. Of course, increasing the vertical dimensions of the mid-bass horn mouth will improve vertical pattern control. Unfortunately, the entire system of bass driver, mid bass, and high frequency then grows correspondingly larger.

This frequently produces a system that has the advantage of improved directivity, but also has the disadvantage of being too large for the lines of sight or aesthetic considerations in the venue. Typically, a venue requires wide horizontal and a narrow vertical dispersion to properly cover the audience. Many popular venues require coverage in the horizontal plane of 80° to 120°, and vertical patterns of 40° to 60°. This restricted vertical pattern will provide proper audience coverage and will limit ceiling reflections, plus will minimize spill directed beneath the speaker towards the performing area.

Line Arrays and Overlapping

Control of low-frequency vertical directivity can also be accomplished through the use of vertical line arrays as well as large format horns. Like a large-mouth horn, a vertical line array of sufficient dimensions can be used very successfully to extend directivity control and substantially improve overall intelligibility.

An overlapped combination of bass driver(s) and mid-bass horn can also be used to produce a line array. This produces a larger "effective" vertical-radiating dimension that extends directivity control down to lower frequencies. This technique of overlapping individual devices will not only improve directional control, but also make more effective use of the optimum performance of each device.

A representative idealized crossover frequency response for a conventional "non-overlapped" three-way concert system is shown in Fig. 1. The crossover is a conventional design where the bass to mid-bass (or midrange) crossover occurs at 125 Hz, and the mid-bass to high-frequency transition is at 1.7 kHz. With the typical 0.5 x 0.5 m (20 x 20 in.) mid-bass horn mentioned previously and this crossover, this system would exhibit unacceptably broad coverage below 500 Hz. It simply looses its ability to control directivity when the wavelengths become longer than the radiating dimensions.

The system of Fig. 1 can be converted to a version that has much improved upper-bass and lower-midrange coverage control by overlapping the responses of the bass and midrange sections. This is accomplished by operating the system's woofer higher in frequency so that its response overlaps the bottom part of the mid-bass (or midrange) response. This lets the system's woofer operate higher in frequency than it would normally in a conventional crossover configuration.

The three-way crossover of Fig. 1 can be modified to include the overlap between the bass and midrange. The idealized response of the modified crossover is shown in Fig. 2. In this situation, the bass driver operates from 30 Hz up to 540 Hz and overlaps the midrange section from 125 to 540 Hz. The 6-dB shelf between 125 Hz and 540 Hz is required so that the overlapped drivers sum acoustically to the same reference level as the rest of the system. The mid-bass horn is operated between 125 Hz and 1.7 kHz. Above 1.7 kHz, the HF driver operates alone. The mid-bass section can't be extended below 125 Hz, because its power handling is much reduced in this range and its distortion is significantly higher. Note that just simply raising the crossover frequency of Fig. 1 will not work with a single woofer system, because the woofer's radiation pattern is much too wide. Both the bass and midrange must operate together to increase directivity and reduce the vertical beamwidth.

Of course, in order for the system to sum properly in the overlapped frequency span, the acoustic outputs of the individual bass and midrange sections must be solidly in phase throughout the overlapped region. This minimizes the lobing error of the system [2] and ensures that the main directional beam faces straight ahead in the overlapped region. The in-phase condition also ensures that the individual outputs sum to a 6-dB higher level.

The bass/mid-bass overlap region significantly narrows the lower mid-bass vertical coverage of the system and increases the directivity. The response overlap and the resultant reduction of vertical coverage and directivity increase will produce substantial intelligibility improvements in reverberant environments.

Implementation Using Electronic Crossover Signal Processing

Implementation of the overlap scheme requires careful control of the crossover drive signals to the individual speaker sections. This essentially precludes the use of passive networks and requires the use of electronic processing. Almost any conventional digital crossover/loudspeaker management system can generate the response magnitude shapes shown in Fig. 2. Unfortunately, the results may be much less than optimal because the acoustic outputs of the sections may sum incorrectly in the overlap region, due to crossover and driver phase-shifts and delays. Crossovers and speakers exhibit non-constant time delays that vary with frequency and the steepness of their response roll-off, and may exhibit non-minimum phase behavior. The consequences of these variations are incorrect summing and lobing errors that result in frequency-dependent polar response shifts.

To attain the proper phase relationships for proper overlap summing, the crossover signal processor must include capability to manipulate phase independent of signal magnitude. In addition to variable delay, which is common in all DSP-based crossovers, the processor must include first-and second-order all-pass filter capability, which is not very common.

Measurements

This section describes measurements on the effect of crossover overlap on two different sound-reinforcement speaker systems. The DSP-based Merlin ISP-100 Integrated Signal Processor provided the processing to configure both systems in both the conventional non-overlap and overlap crossover modes. Measurements of frequency response, 6-dB-down beamwidth, and directivity are described. All measurements were done in Electro-Voice's large anechoic chamber. The beamwidth and directivity information was calculated from full-sphere polar data taken at 2° increments at a distance of 6 m (19.7 ft.) from the speaker.

Speakers Measured

Two different models of full-range concert speaker systems from the Electro-Voice® X-Array™ Install sound reinforcement speaker line: models Xi-1153/64F and Xi-2153/64F were measured.

Read more about X-Array Install (Xi Series) loudspeakers.

Xi-1153/64F Di-Pole Two-Element Line Array System

The Xi-1153/64F is a three-way system with a 15-inch direct-radiator driver slot-loaded vented-box low-frequency section, a 12-inch driver horn-loaded midrange, and a compression driver feeding a 60° x 40° constant-directivity HF horn. The system has a net weight of 93.0 kg (205 lbs.) and has dimensions: 914 mm (36.00 in.) H, 586 mm (23.07 in.) W (front), 354 mm (13.93 in.) W (back), 759 mm (29.88 in.) D. A front view of this system is shown in Fig. 3

Read the Xi-1153/64 data sheet.
(Note: This product has been discontinued.)

Xi-2153/64F Tri-Pole Three-Element Line Array System

The dual 15-inch woofer three-way Xi-2153/64F system is essentially the same as the Xi-1153/64F but contains an additional slot-loaded vented-box woofer on the opposite end. As a result, the height of the system increases from 914 mm (36.00 in.) to 1233 mm (48.54 in.). The midrange and high-frequency portions of the system are exactly the same as the Xi-2153/64F system. The system has a net weight of 113.4 kg (250 lbs.) and has dimensions of 1233 mm (48.54 in.) H, 586 mm (23.07 in.) W (front), 354 mm (13.93 in.) W (back), 759 mm (29.88 in.) D. A front view of this system is shown in Fig. 4.

Read the Xi-2153/64 data sheet.

Measurement Results

Xi-1153/64F

Figure 5 shows the Xi-1153/64F's 6-dB-down beamwidth (a) and directivity (b) of this system when it is driven in the non-overlapped conventional mode with crossovers at 125 Hz and 1.75 kHz. Note that below 630 Hz, the system's horizontal and vertical coverage widens uncontrollably passing through 100° at 500 Hz and 200° at 200 Hz. The directivity is correspondingly low below 630 Hz.

Figure 6 shows the beamwidth (a) and directivity (b) versus frequency of the same system when driven in the overlapped mode. When compared to the beamwidth and directivity data of the system operated in the non-overlapped mode (Fig. 5), the overlapping provides a significant narrowing of vertical beamwidth and increase in directivity between 160 and 800 Hz.

Figure 7 shows the individual crossover-driven frequency response curves of the bass (LOW), midrange (MID), and high-frequency (HIGH) sections of the Xi-1153/64F system operated in the overlap configuration. The measurements were taken with the microphone placed three meters on the system's high-frequency horn axis.

Note the overlap region that extends from about 150 to 500 Hz. Between 150 and 250 Hz, the LOW and MID levels are essentially exactly the same. However, as compared to the idealized crossover curves shown in Fig. 2, the overlap region is narrower. Above 250 Hz, the LOW and MID responses were deliberately made to gradually diverge, so that the system's vertical beamwidth was evened out in the overlap range.

Figure 8 shows the in- and out-of-polarity frequency responses of the system's low-to-mid crossover when operated in the overlap mode. With the LOW section reversed, the response exhibits a deep wide null in the response in the overlap region and a reduction in response from 100 to 800 Hz. This indicates that when connected in normal polarity, the LOW and MID+HIGH responses will be solidly in phase, as desired. In order to get the LOW and MID responses in phase through the overlap region, two first-order all-pass filters were required in the LOW drive, in addition to the normal minimum-phase high-pass, low-pass and parametric filters.

Xi-2153/64F

Figure 9 shows the beamwidth (a) and directivity (b) of the Xi-2153/64F system when it is driven in the non-overlapped conventional mode with crossovers at 125 Hz and 1.76 kHz. As before, note that below 630 Hz the system's horizontal and vertical coverage widens uncontrollably. The directivity is correspondingly low below 630 Hz.

When overlapped with the woofer crossover low-pass filter moved from 125 up to 540 Hz, Fig. 10 shows the beamwidth (a) and directivity (b) of the system. Note the improvement in directivity and considerable reduction in vertical beamwidth. Table 1 compares the directivity and vertical beamwidth of the non-overlapped and overlapped configurations of the Xi-2153/64F system.

Conclusions

Overlapping the bass and midrange sections of a concert speaker system can significantly reduce the vertical beamwidth and increase the directivity in the upper-bass and lower-midrange frequency bands. To properly implement the overlap scheme, requires an electronic crossover/processor that provides all-pass filters so that phase can be manipulated independent of response magnitude. This capability is required to insure that the individual bass and midrange responses are exactly in phase through the overlap region to minimize lobing error and polar response tilting.

Proper processing of the crossover of a concert speaker to introduce overlap in the responses of the bass and midrange can result in very audible improvements in system performance. The increase in directivity (higher Q) and reduced vertical coverage greatly contributes to improved vocal intelligibility, which can easily be demonstrated in reverberant spaces.

References

[1] D. B. Keele, Jr., "What's So Sacred About Exponential Horns?," Presented at the 51st Convention of the Audio Engineering Society, Preprint No. 1038 (F-3), (May 1975).

[2] S. P. Lipshitz and J. Vanderkooy, "A Family of Linear-Phase Crossover Networks of High Slope Derived by Time Delay," *J. Audio Eng. Soc.*, vol. 31, pp.2-20 (1983 Jan./Feb.)

Table 1. *Comparison of vertical beamwidth and directivity between non-overlapped and overlapped modes of operation for the Xi-2153/64F.*

Frequency Hz	Non-Overlapped			Overlapped		
	Directivity Q	Directivity Index Di, dB	Vertical Beamwidth Degrees	Directivity Q	Directivity Index Di, dB	Vertical Beamwidth Degrees
160	2.9	4.6	142	3.0	4.7	86
200	3.4	5.3	150	4.3	6.3	69
250	4.3	6.4	111	5.3	7.2	61
315	4.2	6.3	100	6.6	8.2	59
400	4.4	6.5	116	8.4	9.3	57
500	6.2	7.9	102	12.4	10.9	51
630	10.4	10.2	84	17.3	12.4	54
800	16.3	12.1	60	18.3	12.8	49
1 k	17.5	12.4	52	20.4	13.1	41

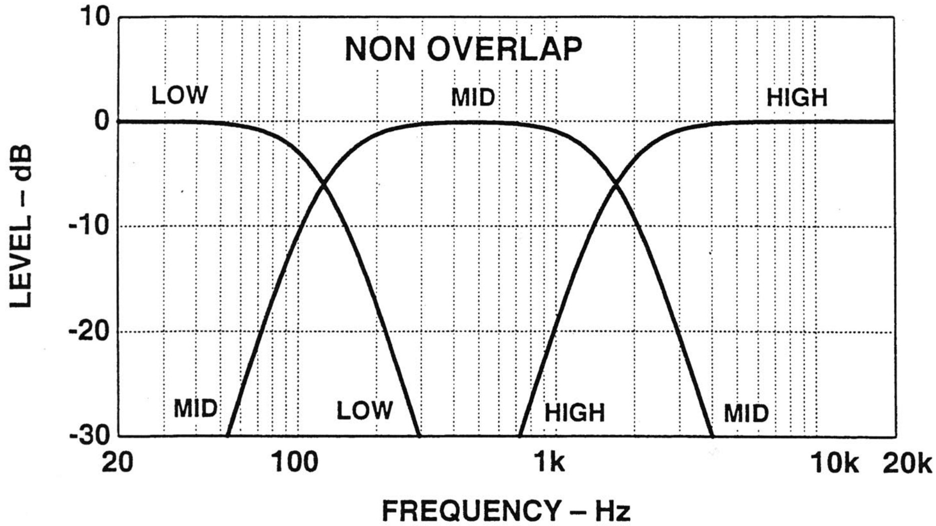

Figure 1. *Magnitude frequency responses of an idealized three-way conventional crossover.*

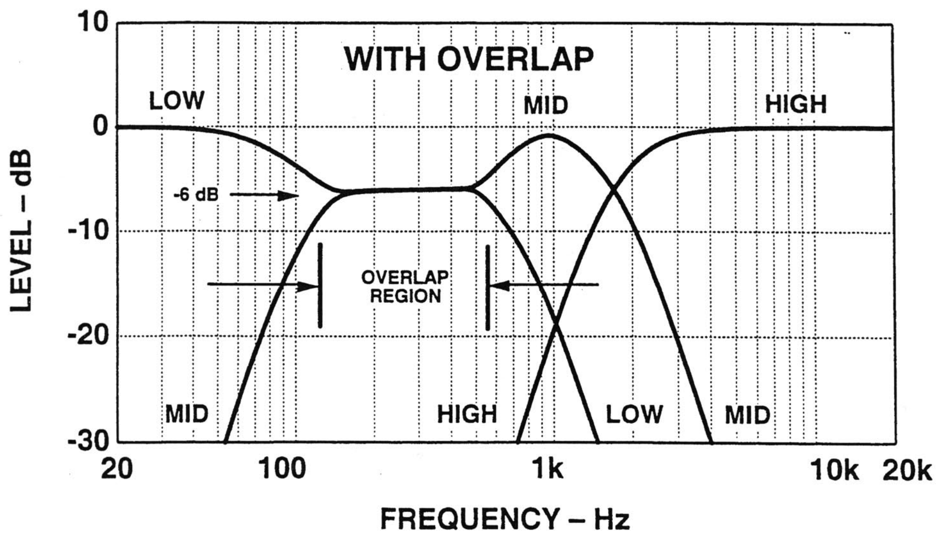

Figure 2. *Magnitude frequency responses of an idealized three-way crossover implementing overlap between woofer and midrange sections.*

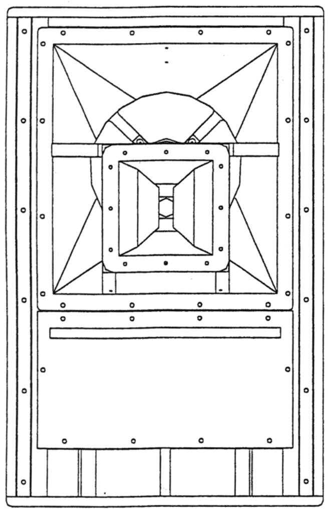

Figure 3. *Front view of Xi-1153/64F X-Array Install single-woofer three-way full-range sound reinforcement speaker system.*

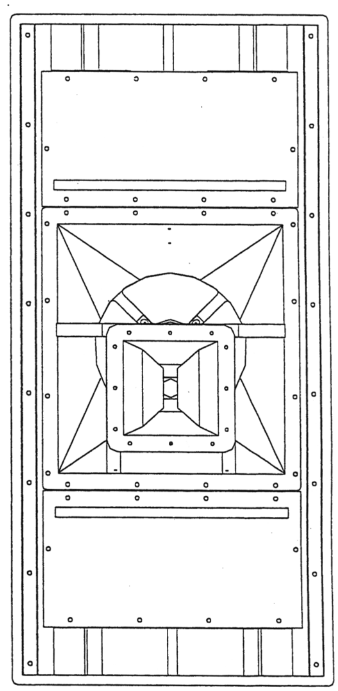

Figure 4. *Front view of Xi-2153/64F X-Array Install dual-woofer three-way full-range sound reinforcement speaker system.*

NON-OVERLAP

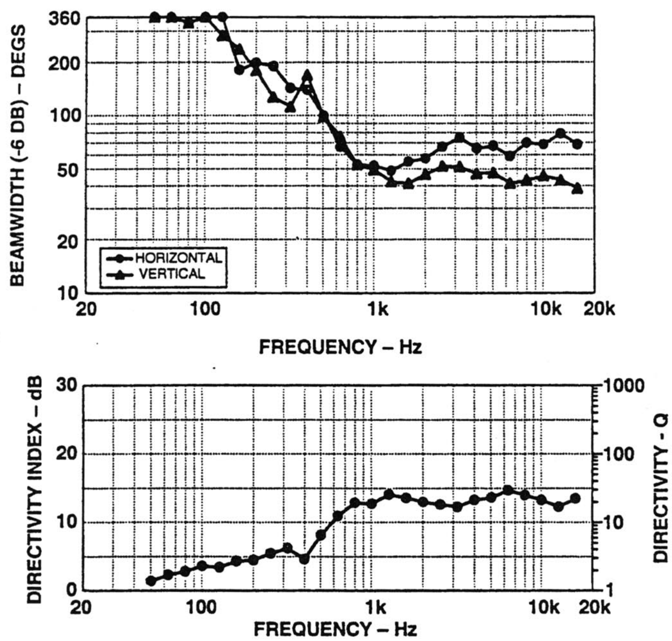

Figure 5. *Beamwidth and directivity of Xi-1153/64F in non-overlap mode. (a) Beamwidth. (b) Directivity.*

OVERLAP

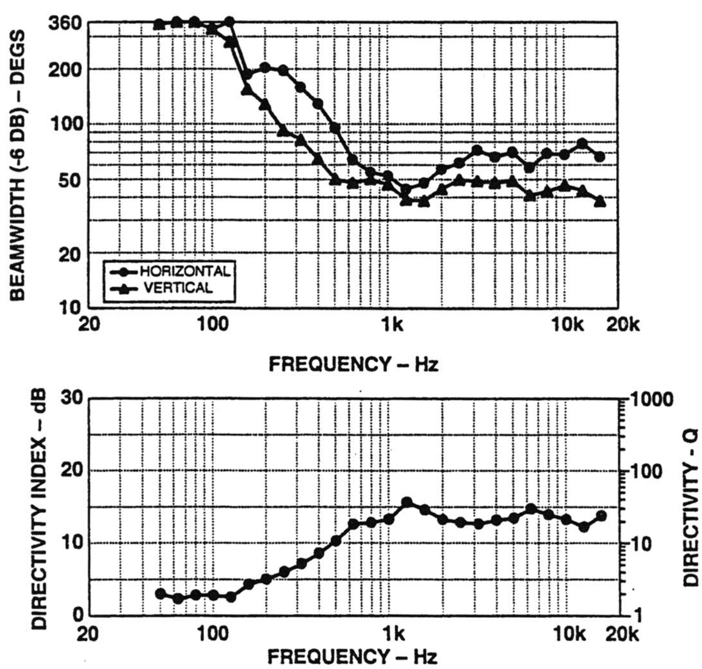

Figure 6. *Beamwidth and directivity of Xi-1153/64F in overlap mode. (a) Beamwidth. (b) Directivity.*

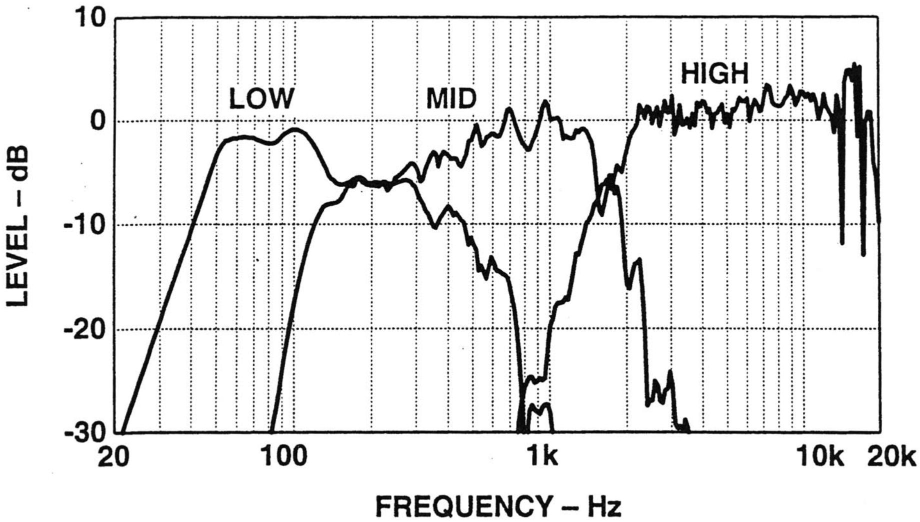

Figure 7. *Individual magnitude frequency responses of drivers of Xi-1153/64F driven by crossover in overlap mode.*

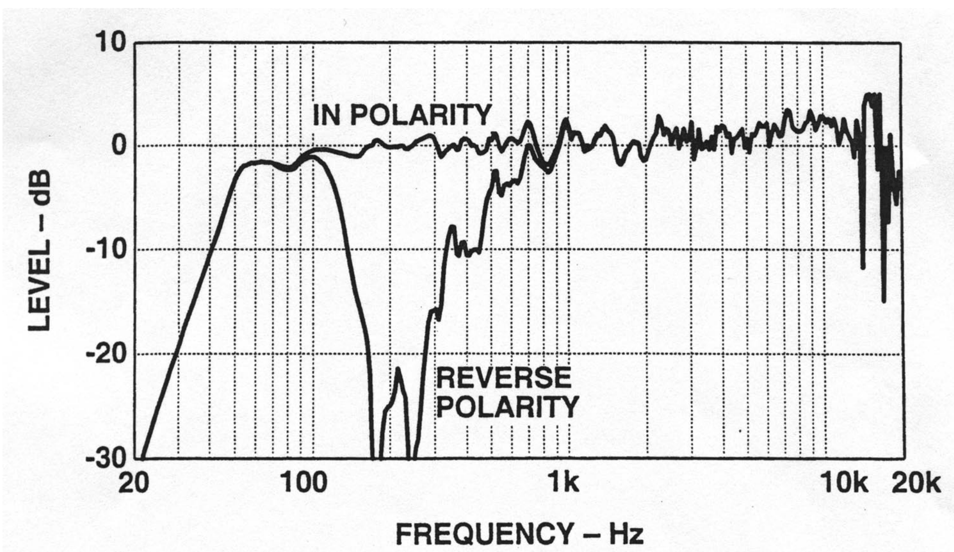

Figure 8. *Magnitude frequency responses of Xi-1153/64F with woofer in- and out-of polarity.*

NON-OVERLAP

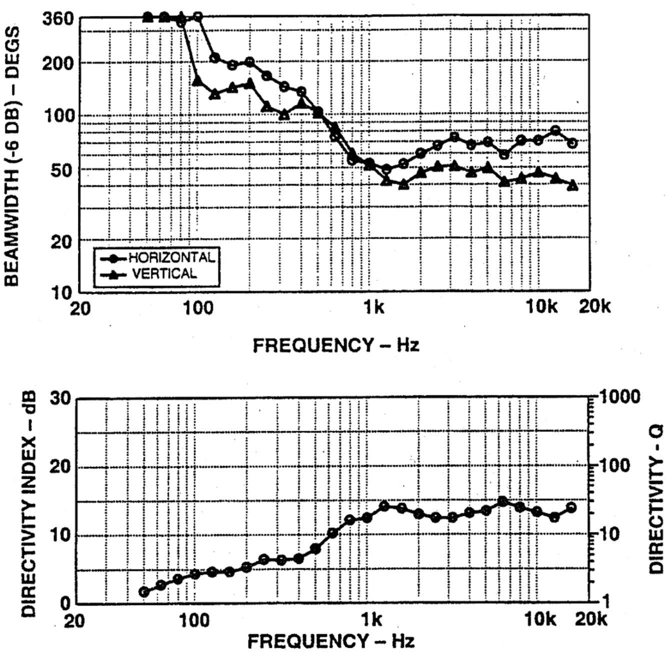

Figure 9. *Beamwidth and directivity of Xi-2153/64F in non-overlap mode. (a) Beamwidth. (b) Directivity.*

OVERLAP

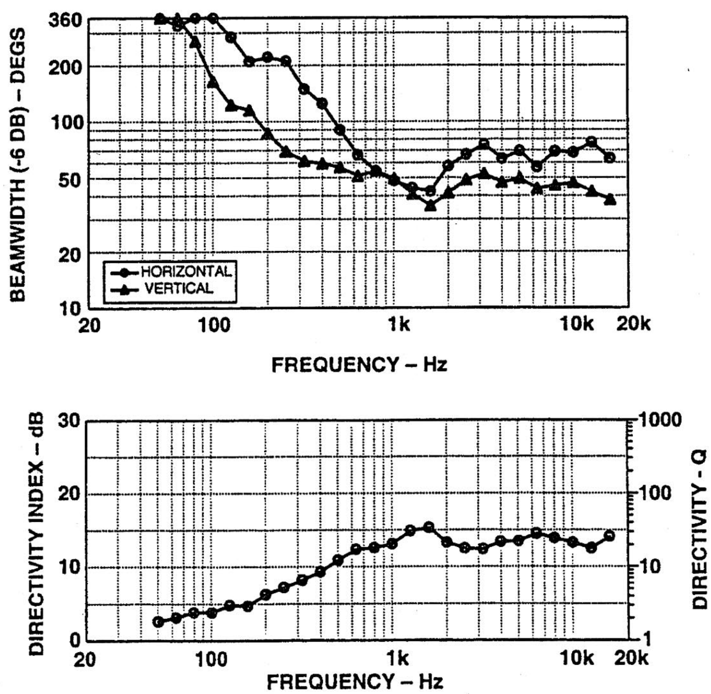

Figure 10. *Beamwidth and directivity of Xi-2153/64F in overlap mode. (a) Beamwidth. (b) Directivity.*