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(71) Applicant: SONY ELECTRONICS INC. [US/US]; 1
Sony Drive, Park Ridge, NJ 07656 (US).

(72) Inventor: ANAGNOS, Daniel, P.; 265 River Road #1,
Grandview, NY 10960 (US).

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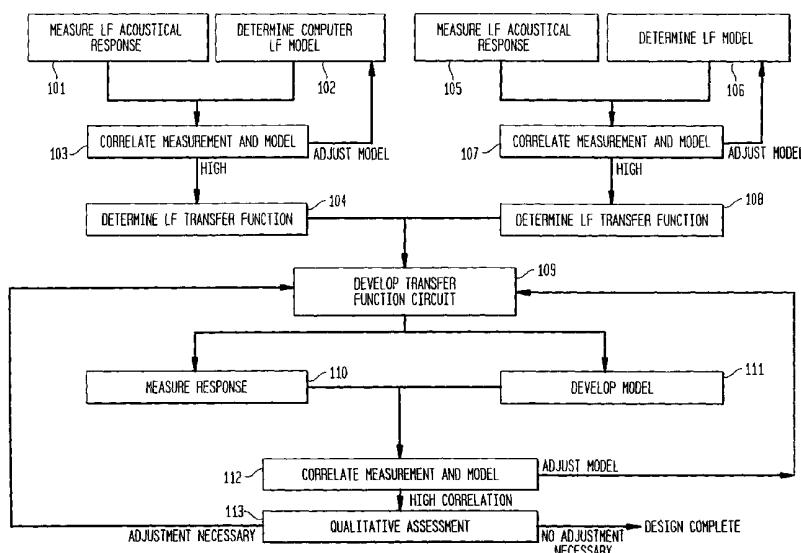
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(54) Title: COMPLEMENTARY TRANSFER FUNCTION DESIGN OF CROSSOVER FILTERS IN LOUDSPEAKER SYSTEMS



(57) Abstract: The invention provides a system and method of designing complementary transfer functions (CTF) [109] for crossover filters that adjust for various crossover considerations. According to the invention, a computer-implemented system and procedure, in a specific audio environment, processes crossover factors [110], designs a CTF filter in a computer simulation [111], correlates measurements of crossover parameters with the computer simulations [112], and adjusts the CTF design [14] until there is a high or predetermined degree of correlation between the computer simulation and the crossover measurements. In particular, the inventive system and method achieves proper blending between chosen sets of subwoofers [105] and satellite speakers [101] in loudspeaker systems.

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COMPLEMENTARY TRANSFER FUNCTION DESIGN OF
CROSSOVER FILTERS IN LOUDSPEAKER SYSTEMS

FIELD OF INVENTION

5 The present invention is in the field of crossover filter design in
loudspeaker systems.

BACKGROUND OF INVENTION

 The frequency range of human hearing spans from about 20 Hertz (Hz) to
20 kilo-Hertz (kHz). In order to reproduce music in this frequency range, it is
10 desirable for the loudspeaker system to reproduce the full audio spectrum.
However, most loudspeakers are incapable of accurately reproducing the entire
audio spectrum in the range of 20 Hz to 20 kHz. One approach to this problem is
the use of a combination of one or more low-frequency (LF) speakers, i.e.,
subwoofers, which are designed specifically for clear sound reproduction in the LF
15 range, and one or more satellite speakers, which are designed to maintain a wide
dispersion pattern in the mid- and high-frequency (HF) ranges. Such a
combination of speakers in different audio ranges can reproduce the full audio
spectrum for human hearing. However, configuring a loudspeaker system with
separate speakers designed for different audio ranges has its drawbacks. In
20 general, the different speakers have different audio sensitivities and dispersion

characteristics. Good LF reproducing speakers tend to perform poorly in the HF range and, similarly, good HF reproducing speakers generally perform poorly in the LF range. Since HF speakers tend to be more sensitive than LF speakers, the satellite speakers would have greater loudness amplitude than the subwoofers. The power-handling capabilities of HF speakers is also quite limited, because signals at the LF range can drive the HF speakers through very large displacements and can damage the speaker unit at significant power levels. Furthermore, in the range where the frequency response of the LF and HF speakers overlap, there usually exists either a large rise or a large dip in sound pressure amplitude (measured in decibels, or dB) and significantly large phase anomalies and discontinuities. This is usually perceived as a “lack of blending or coherence” between the subwoofers and the satellite speakers.

In addition to power handling and loudness amplitude problems, crossover design can solve problems resulting from the frequency response overlap by filtering out the low frequencies from signals being applied to the HF speakers, and by filtering out the high frequencies from signals being applied to the LF speakers. There are two distinct ways to implement a loudspeaker crossover: passive and active design. Passive crossover design employs only passive electrical components (such as resistors, capacitors and inductors) and acts directly on the speaker level signal from the power amplifier. The main advantage of passive crossover design is that it allows one power amplifier to drive a complete full-

range loudspeaker system. However, passive designs are usually forced to cross over at relatively high frequencies (above 150 Hz) because of physical constraints of component size and power handling considerations. As a result, audio reproduction performance of loudspeaker systems with passive crossover design at
5 very low frequencies (below 150 Hz) is generally inferior to active crossover designs because of component non-linearities and signal distortion.

The alternative to a passive crossover design is active design. Active crossover design uses electrical or electronic filters to modify the frequency response of signals being applied to the speakers. In a two-way system, for
10 example, a full-spectrum signal passes through a high-pass filter (HPF) on the way to the HF speakers while the signal to the LF speakers passes through a complementary low-pass filter (LPF). The HPF passes signal information above a selected frequency, referred to as the crossover frequency, and attenuates the components of the signal that fall below the crossover frequency. Similarly, the
15 LPF passes information below the crossover frequency and attenuates frequency components above the crossover frequency. Proper selection of the crossover frequency is essential for delivering a smooth, flat response in the audio spectrum.

In an ideal system, the crossover filter directs all signal information above the crossover frequency to the HF speakers and all signal information below the
20 crossover frequency to the LF speakers. The crossover filter ideally would serve to attenuate the HF response of the subwoofers -- by minimizing the levels of signals

input to the subwoofer at frequencies above the crossover frequency. However, in passive crossover designs, the LPF, has a significant series resistance which affects the LF response of the subwoofer. This series resistance can act to reduce the damping factor of the amplifier and therefore raise the total “Q” factor of the subwoofer system. More significantly, however, is the effect upon the subwoofer transducer itself, skewing the Thiele/Small design parameters such that the system becomes de-tuned. The results of these two effects can produce a peaked or shelved LF response, which is highly undesirable.

Another consideration is the “slope” of the crossover filter. Crossover filters have the characteristic that for each frequency octave beyond the crossover point, the response of the filter is reduced by a certain amount. This characteristic is referred to as the slope of the filter. Typical crossover filters have slopes of 6, 12, 18 or 24 dB per octave. In other words, the crossover filter reduces the response by 6, 12, 18 or 24 dB with each octave change in frequency beyond the crossover point. As an example, in a system with a pair of filters with a crossover frequency at 1 kHz and a filter slope of 18 dB per octave, the response of each filter is down 3 dB at the crossover point. Above 1 kHz the crossover slope reduces the response of the LF speaker at a rate of 18 dB per octave. This means that at 2 kHz the response of the woofer is reduced by 18 dB and at 4 kHz the response is reduced by 36 dB, compared to the response at the crossover frequency at -3 dB. Likewise, the response of the HF speaker is reduced by 18 dB at 500 Hz

and by 36 dB at 250 Hz. In comparison, a 6-dB-per octave crossover slope reduces the response of the LF speaker only by 12 dB at 4 kHz and the response of the HF speaker is down only by 12 dB at 250 Hz. Because of power handling considerations in the HF speaker, the sharper crossover slope of 18 dB per octave
5 allows the use of a lower crossover frequency than either 6- or 12-dB-per-octave filter slopes. In other words, because of filter slope, for a given crossover frequency, the smaller the filter slope utilized in the crossover, the greater the power handling capability required for an HF speaker.

Existing loudspeaker systems with active crossover design are capable of
10 establishing a crossover point at very low frequencies (as low as 30 Hz) and offer varying degree of adjustability in filter crossover frequency, level, phase, slope and Q. This adjustability feature is essential for ensuring a flat response, or audio blending of sounds in different frequency ranges in multi-way loudspeaker systems. The problem with such existing systems is that, even with significant
15 adjustment freedom and flexibility, the transfer functions of the crossover filters are not correct for proper blending. General purpose transfer functions are utilized because of the complexity and difficulty in designing and implementing specialized transfer functions. Exemplary general purpose transfer functions include Bessel, Butterworth and Linkwitz-Riley. See pp. 12-5 through 12-29,
20 *Electronics Engineers' Handbook*, 3d Ed., Donald G. Fink and Donald Christiansen, eds., which is incorporated by reference herein. However, general

purpose transfer functions are exceedingly difficult to adjust, e.g., by the end user, in a subwoofer/satellite loudspeaker system in a specific audio environment, to obtain satisfactory blending and overall performance. The adjustment process often involves a great deal of empirical data gathering and trial-and-error tests in order to configure a crossover filter best suited for a specific audio environment. Conducting empirical analysis and tests becomes increasingly cumbersome and time-consuming in more complex systems. Because the final system adjustability cannot account for the transfer functions of the individual loudspeakers (which will combine with the transfer functions of the filters), it remains unlikely that satisfactory performance will be attained using generalized filters.

Specialized transfer functions designed for specific audio environments or fixed sets of LF and HF speakers can partially eliminate some of the aforementioned disadvantages of general purpose transfer functions. However, configuring specialized transfer functions, as they are designed with a fixed set of parameters, also limits the choice of satellite speakers. Pre-configured specialized transfer function filters for crossover purposes put constraints on system design when the existing system provides only predetermined choices of subwoofers and satellite speakers.

There is therefore a need in the art of loudspeaker system design for a computer-implemented system and method that can create complementary transfer functions (CTF) and associated filters with adjustability in respect to factors

affecting CTF and filter considerations. There is a need for a system and method of design procedure that allows ideal blending between chosen sets of subwoofers and satellite loudspeakers. In short, a speaker design system and method is needed that self-corrects CTF design parameters when configuring crossover filters,
5 without the aforementioned disadvantages of cumbersome empirical analysis and tests.

SUMMARY OF THE INVENTION

The present invention is related to crossover filter design in loudspeaker systems. In particular, the invention is a method of designing complementary
10 transfer functions in crossover filters for subwoofer and satellite loudspeakers which in combination deliver a flat amplitude response and smooth, integrated phase response across the audio spectrum.

The invention is a unique system and method of designing complementary transfer functions (CTF) for crossover filters that adjust for various crossover
15 considerations. According to the invention, a computer-implemented system and procedure, in a specific audio environment, processes crossover factors, designs a CTF filter in a computer model, correlates measurements of crossover parameters with the computer model, and adjusts the CTF design until there is a high or predetermined degree of correlation between the computer model and the crossover
20 measurements. The invention eliminates the need for lengthy, cumbersome empirical data gathering and trial-and-error analysis in the final end-user

adjustment process. In particular, the inventive system and method achieves proper blending between chosen sets of subwoofers and satellite speakers in loudspeaker systems. The invention greatly reduces development time, while improving the quality and completeness of the final design result.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1 illustrates the method and procedure for complementary transfer function (CTF) design in crossover filters with low-pass filters only.

Figure 2 illustrates the method and procedure for CTF design in crossover filters with low-pass filters and high-pass filters.

10 Figures 3A and 3B are schematics of different embodiments of the invention in an analog and a digital loudspeaker system, respectively.

DETAILED DESCRIPTION

Preferred embodiments of the invention are hereinafter described. It is noted that, while the system and method of designing complementary transfer
15 functions (CTF) for crossover filters is implemented at the electrical circuit level for the preferred embodiments, that should be viewed as a particular way of implementing the invention which does not to limit the scope of the invention. It will readily be seen by those skilled in the art that this CTF design system and method could be implemented with analog loudspeaker systems as well as with

digital signal processing (DSP) in digital systems. In addition, the preferred embodiments are presented in the context of a two-way loudspeaker system in a fixed audio environment such as a typical half-space room. It is intended that the principles of the invention be applied for multi-way loudspeaker systems in any
5 audio environment or channelization arrangement.

The preferred embodiments disclosed hereinafter operate in a certain audio environment with pre-determined parameters. Specific parameters such as the damping factor, level are pre-determined before implementing the design system and method according to the invention. Such pre-determined parameters also
10 include operation in a typical home environment such as a half-space room in which the wavelengths of sound near the crossover frequency region are large relative to the room dimensions. For the preferred embodiment, all acoustical measurements are made at a fixed reference point in an anechoic environment for frequencies above 200 Hz, such as an exemplary reference point at 3 meters, on-
15 axis, and at a listening height of one meter. Moreover, half-space acoustical loading of speaker output is assumed for both subwoofers and satellite speakers at all frequencies below 200 Hz (including the system crossover frequency). The crossover frequency at which the preferred embodiments are implemented is set at or below 80 Hz. The difference in phase response between corner loading and
20 center room loading is minimal as a result of the aforementioned parameters. Note that satellite speakers in all preferred embodiments hereinafter disclosed can either be passive or active. A passive satellite speaker only uses passive components

(e.g., resistors, capacitors, inductors) to divide the energy (supplied from an amplifier) between the individual transducers in the loudspeaker system. In contrast, an active satellite speaker uses low-level, electronic components (including transistors, integrated circuits or vacuum tubes) to divide the energy
5 between individual amplifiers and transducers in a loudspeaker system.

The system and method of the invention are hereinafter particularly described with respect to several illustrative embodiments. The first such illustrative embodiment, a system and method of crossover design in CTF filters, utilizing low-pass filters only, is depicted schematically in Figure 1. In this
10 embodiment, the active filtering is provided only for the subwoofer, utilizing a low-pass filter (LPF).

As will be seen in the figure, the methodology for this embodiment begins with a measurement of the acoustical response of an LF and an HF speaker to be operated in combination and comparison of such responses with predicted
15 responses based on a computer model for that speaker using a trial transfer function. Considering the specific steps of the methodology, in Step 101, measurements are obtained for the acoustical response of the satellite (HF) speaker of a given two-way loudspeaker system in a typical half-space room. Measurements are taken according to the close-miking technique that approximates
20 half-space loading in-room conditions. The invention uses an audio analyzer that performs an MLS-type (i.e., maximum length sequence) acoustical measurement implemented with a pseudo-random noise source and correlated fast Fourier

transform (FFT) calculations. In an exemplary measurement according to the close-miking technique, microphones are placed at 1.5 mm from the center of each low-frequency (LF) transducer in the speaker, with an input voltage of 2.83 volts. The acoustical parameters measured are amplitude and phase versus frequency
5 from 10 Hz to 500 Hz. The data are then exported from the audio analyzer to the correlation stage in Step 103 for comparison with the response generated by the computer simulated model in Step 102.

In Step 102, the computer LF model of the selected satellite loudspeaker in such a typical half-space room is formulated. Such a computer model can be
10 formulated with conventional computer-simulated loudspeaker analysis tools such as LEAP (Loudspeaker Enclosure Analysis Program), sold by Linear X Systems, Inc. of 9500 Tualatin-Sherwood Road, Tualatin, Oregon 97062 USA. In Step 103, the response generated by the computer simulated model is compared and correlated with the acoustical response of the satellite speaker. Based on such
15 correlation, the computer LF model formulated in Step 102 is adjusted at Step 10 until a high or predetermined degree of correlation is reached. Adjustments to the computer simulated model which are made to obtain an acceptable correlation with the acoustical measurements are performed manually. At this point, parameters of the computer model in the simulation program (such as LEAP) are adjusted by the
20 system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

Acceptable correlation is reached when the measurements agree within ± 1 dB in amplitude with the simulation of the computer model. Moreover, phase measurements must agree within ± 15 degrees with the simulation of the computer model. Note that the correlation bandwidth is 10 Hz to 500 Hz. In Step 104, because there is a high or predetermined degree of correlation, parameters in the computer model become the basis for configuring the LF transfer function of the satellite loudspeaker in the two-way system. The overall acoustical transfer function of the satellite speaker is determined and accounted for in the design embodied in the present invention.

Similarly, considering the specific steps of the methodology in Step 105, measurements are obtained for the acoustical response of the subwoofer (LF) speaker of the two-way loudspeaker system in a typical half-space room. Acoustical response measurements of the subwoofer speaker are taken in a similar fashion as those of the subwoofer satellite speaker. Measurements are taken according to the close-miking technique that approximates half-space loading in-room conditions. The invention uses an audio analyzer that performs an MLS-type (i.e., maximum length sequence) acoustical measurement implemented with a pseudo-random noise source and correlated fast Fourier transform (FFT) calculations. In an exemplary measurement according to the close-miking technique, microphones are placed at 1.5 mm from the center of each low-frequency (LF) transducer in the speaker, with an input voltage of 2.83 volts. The acoustical parameters measured are amplitude and phase versus frequency data

from 10 Hz to 500 Hz. The data are then exported from the audio analyzer to the correlation stage in Step 107 for comparison with the response generated by the computer simulated model in Step 106.

In Step 106, the computer LF model of the selected subwoofer loudspeaker
5 in such a typical half-space room is formulated. In Step 107, the response generated by the computer simulated model is compared and correlated with the acoustical response of the subwoofer speaker. Based on such correlation, the computer LF model formulated in Step 106 is adjusted at Step 12 until a high or predetermined degree of correlation is reached. Adjustments to the computer
10 simulated model which are made to obtain an acceptable correlation with the acoustical measurements are performed manually. At this point, parameters of the computer model in the simulation program (such as LEAP) are adjusted by the system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

15 Acceptable correlation is reached when the measurements agree within ± 1 dB in amplitude with the simulation of the computer model. In addition, phase measurements must agree within ± 15 degrees with the simulation of the computer model. Note that the correlation bandwidth is 10 Hz to 500 Hz. In Step 108, because there is a high or predetermined degree of correlation, parameters in the
20 computer model become the basis for configuring the LF transfer function of the subwoofer loudspeaker in the two-way system. The overall acoustical transfer

function of the subwoofer speaker is determined and accounted for in the design embodied in the present invention.

In Step 109, based on the adjusted LF transfer functions formulated in Steps 104 and 108, a complementary transfer function (CTF) low-pass filter (LPF) circuit is developed. In Step 110, measurements of the acoustical response of the satellite/subwoofer loudspeaker system implemented with the CTF LPF circuit developed in Step 109 are taken in a typical half-space room audio environment. In Step 111, a computer model is formulated for a satellite/subwoofer loudspeaker system implemented with the CTF LPF circuit developed in Step 109. In Step 112, the response generated by the computer simulated model is compared and correlated with the acoustical response of the satellite/subwoofer loudspeaker system. Based on such correlation, the computer model formulated in Step 111 is adjusted at Step 114 until a high or predetermined degree of correlation is reached. Adjustments to the computer simulated model which are made to obtain an acceptable correlation with the acoustical measurements are performed manually. At this point, parameters of the computer model in the simulation program (such as LEAP) are adjusted by the system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

In Step 113, a qualitative assessment of audio reproduction performance is conducted on the satellite/subwoofer system being developed. This step examines quality factors such as harmonic and intermodulation distortion, dynamic range

(e.g., maximum volume of the speaker), transient response (e.g., quickness of bass response), clarity of bass and midrange reproduction and resolution.

If the quality assessment suggests further adjustment in the CTF LPF circuit, Step 109 is re-initiated and the design process continues through Steps 109, 5 110, 111, 112 and 113. Typically, the crossover frequency or center frequency of the CTF filter is adjusted. The order or slope of the CTF filters can be adjusted as well. When these parameters are adjusted, the computer model determines the correct filter Q and gain. The CTF is determined to be correct when the acoustical output from the subwoofer loudspeaker and the acoustical output of the satellite 10 loudspeaker delivers a sum flat response in terms of sound pressure amplitude, of less than plus or minus 3 dB variation and exhibits a smooth combined phase response. If the quality assessment in Step 113 results in no more adjustments, then the design process is complete.

The second illustrative embodiment, a system and method of crossover 15 design in CTF filters, utilizing low-pass filters and high-pass filters, is depicted schematically in Figure 2. Considering the specific steps of the methodology in Step 201, measurements are obtained for the acoustical response of the satellite speaker of a given two-way loudspeaker system in a typical half-space room. Measurements are taken according to the close-miking technique that approximates 20 half-space loading in-room conditions. The invention uses an audio analyzer that performs an MLS-type (i.e., maximum length sequence) acoustical measurement implemented with a pseudo-random noise source and correlated fast Fourier

transform (FFT) calculations. In an exemplary measurement according to the close-miking technique, microphones are placed at 1.5 mm from the center of each low-frequency (LF) transducer in the speaker, with an input voltage of 2.83 volts. The acoustical parameters measured are amplitude and phase versus frequency data
5 from 10 Hz to 500 Hz. The data are then exported from the audio analyzer to the correlation stage in Step 203 for comparison with the response generated by the computer simulated model in Step 202.

In Step 202, the computer LF (low frequency) model of the selected satellite loudspeaker in such a typical half-space room is formulated. In Step 203,
10 the response generated by the computer simulated model is compared and correlated with the acoustical response of the satellite speaker. Based on such correlation, the computer LF model formulated in Step 202 is adjusted until a high or predetermined degree of correlation is reached. Adjustments to the computer simulated model which are made to obtain an acceptable correlation with the
15 acoustical measurements are performed manually. At this point, parameters of the computer model in the simulation program (such as LEAP) are adjusted by the system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

Acceptable correlation is reached when the measurements agree within ± 1
20 dB in amplitude with the simulation of the computer model. Moreover, phase measurements must agree within ± 15 degrees with the simulation of the computer model. Note that the correlation bandwidth is 10 Hz to 500 Hz. In Step 204,

because there is a high or predetermined degree of correlation, parameters in the computer model become the basis for configuring the LF transfer function of the satellite loudspeaker in the two-way system. The overall acoustical transfer function of the satellite speaker is determined and accounted for in the design embodied in the present invention.

Similarly, considering the specific steps of the methodology in Step 205, measurements are obtained for the acoustical response of the subwoofer (LF) speaker of the two-way loudspeaker system in a typical half-space room. In Step 206, the computer LF (low frequency) model of the subwoofer loudspeaker in such a typical half-space room is formulated. In Step 207, the response generated by the computer simulated model is compared and correlated with the acoustical response of the subwoofer speaker. Based on such correlation, the computer LF model formulated in Step 206 is adjusted until a high or predetermined degree of correlation is reached. Adjustments to the computer simulated model which are made to obtain an acceptable correlation with the acoustical measurements are performed manually. At this point, parameters of the computer model in the simulation program (such as LEAP) are adjusted by the system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

Acceptable correlation is reached when the measurements agree within ± 1 dB in amplitude with the simulation of the computer model. Moreover, phase measurements must agree within ± 15 degrees with the simulation of the computer

model. Note that the correlation bandwidth is 10 Hz to 500 Hz. In Step 208, because there is a high or predetermined degree of correlation, parameters in the computer model become the basis for configuring the LF transfer function of the subwoofer loudspeaker in the two-way system. The overall acoustical transfer
5 function of the subwoofer speaker is determined and accounted for in the design embodied in the present invention.

In Step 209, based on the adjusted LF transfer functions formulated in Step 204, a complementary transfer function (CTF) high-pass filter (HPF) circuit is developed. Similarly, in Step 211, based on the adjusted LF transfer function
10 formulated in Step 208, a CTF low-pass filter (LPF) circuit is developed. In Step 210, measurements of the acoustical response of the satellite/subwoofer loudspeaker system implemented with the CTF HPF and LPF circuits developed in Steps 209 and 211, respectively, are taken in a typical half-space room audio environment. In Step 212, a computer model is formulated for a
15 satellite/subwoofer loudspeaker system implemented with the CTF HPF and LPF circuits developed in Steps 209 and 211, respectively. In Step 213, the response generated by the computer simulated model is compared and correlated with the acoustical response of the satellite/subwoofer loudspeaker system. Based on such correlation, the computer model formulated in Step 212 is adjusted at Step 18 until
20 a high or predetermined degree of correlation is reached. Adjustments to the computer simulated model which are made to obtain an acceptable correlation with the acoustical measurements are performed manually. At this point, parameters of

the computer model in the simulation program (such as LEAP) are adjusted by the system designer. However, adjustments to the complementary transfer function parameters are made automatically by the computer simulation program.

In Step 214, a qualitative assessment of audio reproduction performance is
5 conducted on the satellite/subwoofer system being developed. This step examines quality factors such as harmonic and intermodulation distortion, dynamic range (e.g., maximum volume of the speaker), transient response (e.g., quickness of bass response), clarity of bass and midrange reproduction and resolution.

If the quality assessment necessitates further adjustment in the CTF HPF or
10 LPF circuit, Steps 209 and 211 are re-initiated and the design process continues through Steps 209, 210, 211, 212, 213 and 214. Typically, the crossover frequency or center frequency of the CTF filter is adjusted. The order or slope of the CTF filters can be adjusted as well. When these parameters are adjusted, the computer model determines the correct filter Q and gain. The CTF is determined to be
15 correct when the acoustical output from the subwoofer loudspeaker and the acoustical output of the satellite loudspeaker delivers a sum flat response in terms of sound pressure amplitude, of less than plus or minus 3 dB variation, and exhibits a smooth combined phase response. If the quality assessment in Step 214 results in no more adjustments, then the design process is complete.

20 The satellite loudspeaker in the embodiment in Figure 2 is high-pass filtered or cut off below the crossover frequency. Active filtering is provided for both the subwoofer and the satellite loudspeakers. Acoustical overlap between the

subwoofer and satellite speakers is minimal in this embodiment. Moreover, power handling performance of the satellite speaker is greatly improved in this implementation, while signal distortion is significantly reduced.

Figure 3A is an embodiment of the invention in an analog loudspeaker system. In this embodiment, the complementary transfer function (CTF) filters are designed as active analog electronic circuits which are located within the powered subwoofer. The CTF filters are implemented in the subwoofer itself or within an external processor. After the CTF designs are determined for each of the filters according to the invention, they are implemented in electronic circuits that replace conventional general purpose filters for the subwoofer and satellite speakers in the analog system.

Referring to Figure 3A, the Analog Source 301 inputs signal information into the loudspeaker system. The signal information passes through the Active Analog Circuit for processing in 302, which is a CTF low-pass filter (LPF). The CTF is used in place of the conventional general purpose filter in the subwoofer, before the subwoofer amplifier 303. After amplification at 303, the signal information is output by the subwoofer loudspeaker 304.

Similarly, in an analog loudspeaker system with LPF and high-pass filter (HPF) functionalities, the Analog Source 301 inputs signal information into the system and sends it to the Active Analog Circuit at 305. The CTF HPF in 305 is designed according to the method of the invention as embodied in Figure 2 and is implemented in analog electronic circuitry in the Active Analog Circuit at 305.

After filtering at 305, the signal information is passed on to Amplifier 306 for amplification. The Satellite Loudspeaker at 307 then outputs the signal information.

A variation of the analog loudspeaker system (as in Figure 3A) that can
5 utilize all elements of the present invention is the digital loudspeaker system in Figure 3B. In this digital embodiment, all of the CTF filters are implemented using digital signal processing (DSP), either within a powered subwoofer or within an outboard processor. A DSP implementation of the CTF filters are developed using integrated circuits and software development platforms in accordance to the
10 method of the invention as disclosed hereinabove.

Referring to Figure 3B, the Digital Source at 311 inputs signal information into the system for processing at 312, which is a CTF LPF. After processing and filtering at 312, the signal information is transmitted to the Digital to Analog Converter (DAC) at 313 for conversion into analog information. The analog signal
15 information is amplified at Amplifier 314. The amplified signal information is then output by the Subwoofer Loudspeaker at 315.

Similarly, in a digital loudspeaker system with LPF and HPF functionalities, the Digital Source 311 inputs signal information into the system and sends it to the CTF HPF at 316. The CTF HPF in 316 is designed according to
20 the method of the invention as embodied in Figure 2 and is implemented in digital form. After processing and filtering at 316, the signal information is converted to

analog form by the DAC at 317. The Amplifier at 318 amplifies the signal information for output by the Satellite Loudspeaker at 319.

Through DSP, the digital embodiment of the invention can execute the CTF more precisely and has less errors in matching the required transfer function characteristics than its counterpart in analog form. In addition, the digital embodiment avoids many of the disadvantages of analog circuitry such as penalty in noise, signal distortion, and circuit complexity. Moreover, in the digital format, a limitless number of speakers can be accommodated by the design since the required CTF parameters are completely software determined and easily stored and downloaded to the DSP. The CTF can be continually updated or modified and distributed in software form, e.g., over the Internet or by floppy diskette.

CONCLUSION

The present invention provides a system and method of designing complementary transfer functions for crossover filters in a specific audio environment by processing crossover factors, simulating CTF filters in a computer model, correlating measurements of crossover parameters with the computer model, and adjusting the CTF design until there is a high or predetermined degree of correlation between the computer model and the crossover measurements. The invention eliminates the need for lengthy, cumbersome empirical data gathering and trial-and-error analysis in the final end-user adjustment process. In particular, the invention provides proper blending between chosen sets of subwoofers and

satellite speakers in loudspeaker systems. The invention greatly reduces development time, while improving the quality and completeness of the final design result.

Changes and modifications in the specifically described embodiments can
5 be carried out without departing from the scope of the invention. In particular, the present invention may be used in designing complementary transfer functions (CTF) in crossover filters in a loudspeaker system with chosen sets of subwoofers and satellite speakers in a fixed audio environment. Although preferred embodiments are disclosed herein, they do not limit the scope of the present
10 invention.

I CLAIM:

1. A method of complementary transfer function design of crossover filters for a loudspeaker system including at least one speaker arranged to reproduce audio frequencies above a crossover point ("HF speaker") and at least one speaker
5 arranged to reproduce audio frequencies below the crossover point ("LF speaker"), the method comprising the steps of:

measuring acoustical response of the at least one HF speaker [101];

providing a computer simulation of acoustical response of the at least one HF speaker [102];

- 10 correlating the measured acoustical response and the computer simulation of the at least one HF speaker [103];

measuring acoustical response of the at least one LF speaker [105];

providing a computer simulation of acoustical response of the at least one LF speaker [106];

- 15 correlating the measured acoustical response and the computer simulation of the at least one LF speaker [107]; and

developing a complementary transfer function filter for the loudspeaker system based on resultants of correlating steps for the at least one HF speaker and for the at least one LF speaker [104] [108] [109].

2. The method in claim 1, wherein the correlating step for the at least one HF speaker further comprises the substeps of:

determining whether a degree of correlation at or below a predetermined threshold level has been reached between the acoustical response measurements

5 and the computer simulation of the at least one HF speaker [103]; and,

adjusting the computer simulation of the at least one HF speaker [10] if the threshold correlation has not been reached in the determining step.

3. The method in claim 1, wherein the correlating step for the at least one LF speaker further comprises the substeps of:

determining whether a degree of correlation at or below a predetermined threshold level has been reached between the acoustical response measurements

5 and the computer simulation of the at least one LF speaker [107]; and,

adjusting the computer simulation of the at least one LF speaker [12] if the threshold correlation has not been reached in the determining step for the at least one LF speaker.

4. The method in claim 1, further comprising the steps of:
- measuring acoustical response of the loudspeaker system using the developed complementary transfer function filter [110];
- providing a computer simulation for the loudspeaker system with the
- 5 developed complementary transfer function filter [111];
- determining whether a degree of correlation at or below a predetermined threshold level has been reached between the measured acoustical response and the computer simulation of the loudspeaker system [112]; and
- adjusting the computer simulation of the loudspeaker system [14] if a
- 10 degree of correlation at or below a predetermined threshold level has not been reached in the determining step for the loudspeaker system.
5. The method in claim 4, further comprising the steps of:
- performing an assessment of the loudspeaker system performance relative to predetermined performance criteria [113]; and
- adjusting the complementary transfer function filter based on the
- 5 performance assessment if adjustment is warranted [109].

6. The method in claim 5, wherein the measuring steps for the at least one HF speaker, the at least one LF speaker, and the loudspeaker system, respectively, are performed in a low-frequency region in a typical half-space room [101] [105].

7. The method in claim 1, wherein the complementary transfer function filter in the developing step is a low pass filter [109].

8. The method in claim 1, wherein the developing step develops a complementary transfer function high pass filter [209] and a complementary transfer function low pass filter [211].

9. The method in claim 8, further comprising the steps of:

measuring acoustical response of the loudspeaker system with the developed complementary transfer function high pass filter and the developed complementary transfer function low pass filter [210];

5 providing a computer simulation for the loudspeaker system with the developed complementary transfer function high pass filter and the developed complementary transfer function low pass filter [212];

determining whether a degree of correlation at or below a predetermined threshold level has been reached between the measured acoustical response and the computer simulation of the loudspeaker system [213]; and

adjusting the computer simulation of the loudspeaker system [18] if the threshold correlation has not been reached in the determining step for the loudspeaker system.

10. The method in claim 9, further comprising the steps of:

performing an assessment of the loudspeaker system performance relative to predetermined performance criteria[214];

adjusting the developed complementary transfer function high pass filter based on the performance assessment if adjustment is warranted [209]; and,

adjusting the developed complementary transfer function low pass filter based on the performance assessment if adjustment is warranted [211].

11. The method in claim 10, wherein the measuring steps for the at least one HF speaker, the at least one LF speaker, and the loudspeaker system, respectively, are performed in a low-frequency region in a typical half-space room [201] [205] [301].

5

12. The method in claim 1, wherein the loudspeaker system is an analog system in which the complementary transfer function filter is implemented with active analog electronic circuitry [302].
13. The method in claim 1, wherein the complementary transfer function filter is implemented using digital signal processing [312].
14. The method in claim 1 implemented with predetermined parameters including damping factor and level.
15. The method in claim 5, wherein the performing step [113] examines quality factors including harmonic and intermodulation distortion, dynamic range, transient response, clarity of bass and midrange reproduction and resolution.
16. A system of complementary transfer function crossover filters for a loudspeaker system including at least one speaker arranged to reproduce audio frequencies above a crossover point ("HF speaker") and at least one speaker arranged to reproduce audio frequencies below the crossover point ("LF speaker"),
- 5 comprising:
- means for measuring acoustical response of the at least one HF speaker [101];

- means for providing a computer simulation of acoustical response of the at least one HF speaker [102];
- 10 means for correlating the measured acoustical response and the computer simulation of the at least one HF speaker[103];
- means for measuring acoustical response of the at least one LF speaker [105];
- means for providing a computer simulation of acoustical response of the at least one LF speaker [106];
- 15 means for correlating the measured acoustical response and the computer simulation of the at least one LF speaker [107]; and
- means for developing a complementary transfer function filter for the loudspeaker system based on resultants of the correlation of the at least one HF speaker and the at least one LF speaker [104] [108] [109].
- 20
17. The system in claim 16, wherein the correlating means of the at least one HF speaker further comprises:
- means for determining whether a degree of correlation at or below a predetermined threshold level has been reached between the acoustical response measurements and the computer simulation of the at least one HF speaker [103];
- 5

means for adjusting the computer simulation of the at least one HF speaker
[10] if the threshold correlation has not been reached; and

means for configuring a transfer function for the at least one HF speaker if
the threshold correlation has been reached [104].

18. The system in claim 16, wherein the correlating means of the at least one
LF speaker further comprises:

means for determining whether the threshold correlation has been reached
between the acoustical response measurements and the computer simulation of the
5 at least one LF speaker [107];

means for adjusting the computer simulation of the at least one LF speaker
[12] if the threshold correlation has not been reached for the at least one LF
speaker; and

means for configuring a transfer function for the at least one LF speaker if
10 the correlation threshold has been reached for the at least one LF speaker [108].

19. The system in claim 16, further comprising:

means for measuring acoustical response of the loudspeaker system using
the developed complementary transfer function filter [110];

means for providing a computer simulation for the loudspeaker system with
5 the complementary transfer function filter [111];

means for determining whether a degree of correlation at or below a
predetermined threshold level has been reached between the measured acoustical
response and the computer simulation of the loudspeaker system [112] ; and

means for adjusting the computer simulation of the loudspeaker system if a
10 degree of correlation at or below a predetermined threshold level has not been
reached for the loudspeaker system [14].

20. The system in claim 19, further comprising:

means for performing an assessment of the loudspeaker system
performance relative to predetermined performance criteria [113]; and,

means for adjusting the complementary transfer function filter based on the
5 performance assessment if adjustment is warranted [109].

21. The system in claim 20, wherein the acoustical response measurements for
the at least one HF speaker, the at least one LF speaker, and the loudspeaker
system, respectively, are performed in a low-frequency region in a typical half-
space room [101] [105].

22. The system in claim 16, wherein the complementary transfer function filter developed by the developing means is a low pass filter [109].

23. The system in claim 16, wherein the developing means develops a complementary transfer function high pass filter [209] and a complementary transfer function low pass filter [211].

24. The system in claim 23, further comprising:

means for measuring acoustical response of the loudspeaker system with the developed complementary transfer function high pass filter and the developed complementary transfer function low pass filter [210];

5 means for providing a computer simulation for the loudspeaker system with the developed complementary transfer function high pass filter and the developed complementary transfer function low pass filter [212];

means for determining whether a degree of correlation at or below a predetermined threshold level has been reached between the measured acoustical
10 response and the computer simulation of the loudspeaker system [213]; and

means for adjusting the computer simulation of the loudspeaker system if the threshold correlation has not been reached for the loudspeaker system [18].

25. The system in claim 24, further comprising:

means for performing an assessment of the loudspeaker system performance relative to predetermined performance criteria [214]; and,

means for adjusting the developed complementary transfer function high
5 pass filter based on the performance assessment if adjustment is warranted [209].

26. The system in claim 25, wherein the acoustical response measurements for the at least one HF speaker, the at least one LF speaker, and the loudspeaker system, respectively, are performed in a low-frequency region in a typical half-space room [201] [205].

27. The system in claim 16, wherein the loudspeaker system is an analog system in which the complementary transfer function filter is implemented with active analog electronic circuitry [301] [305].

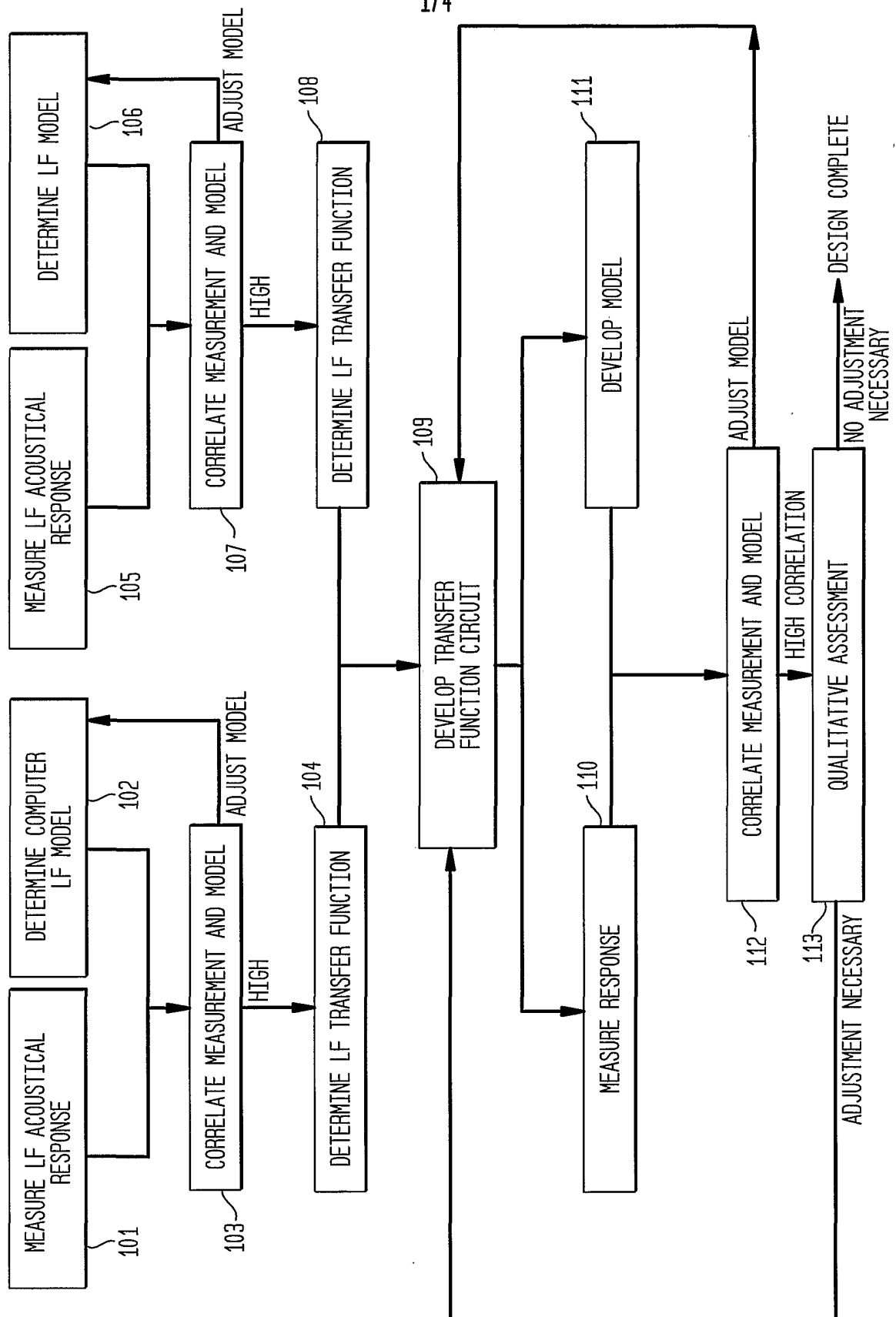
28. The system in claim 16, wherein the complementary transfer function filter is implemented using digital signal processing [312] [316].

29. The system in claim 16 implemented with predetermined parameters including damping factor and level.

30. The system in claim 20, wherein the means for performing a qualitative assessment [214] examines quality factors including harmonic and intermodulation

distortion, dynamic range, transient response, clarity of bass and midrange reproduction and resolution.

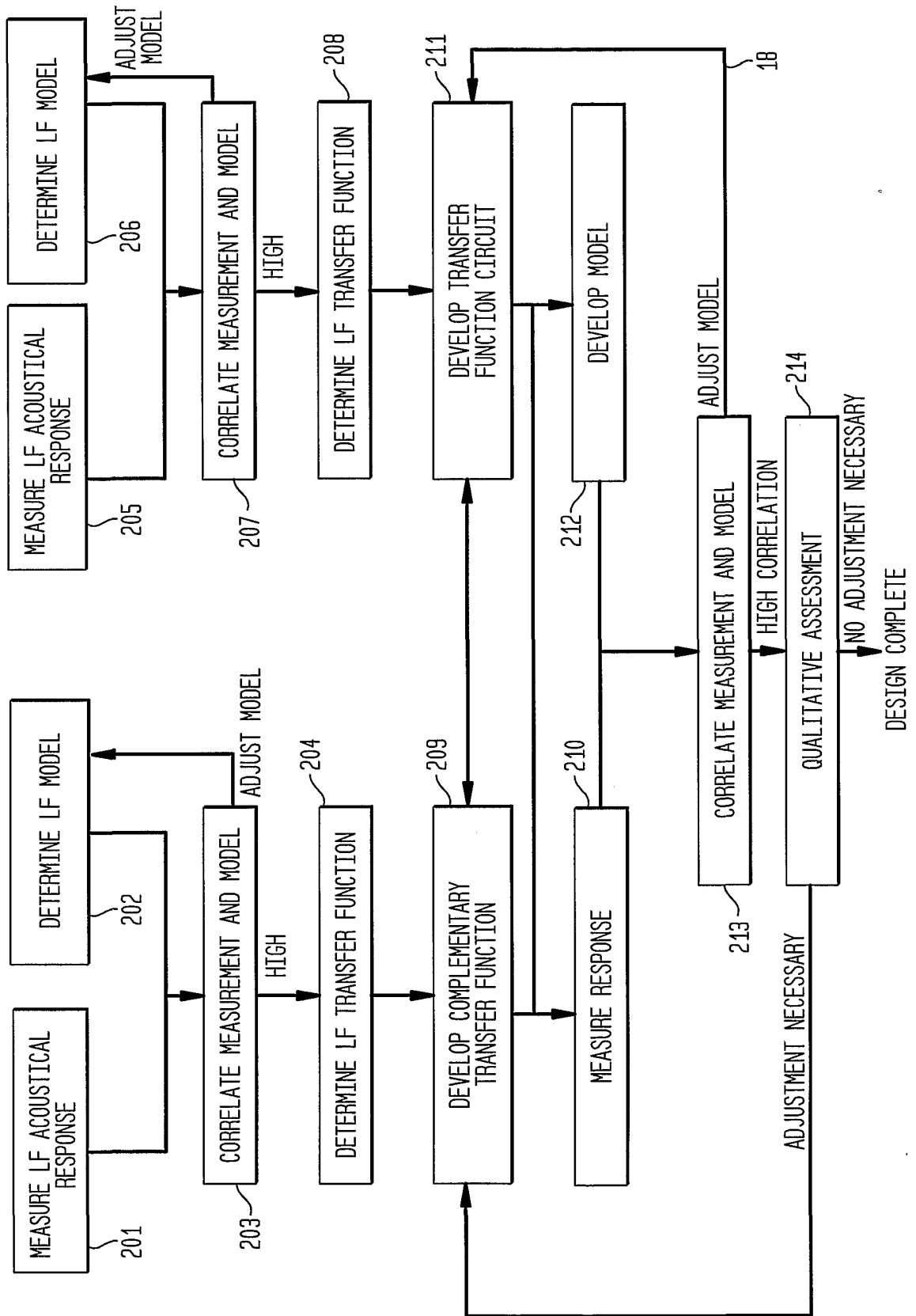
FIG. 1



1/4

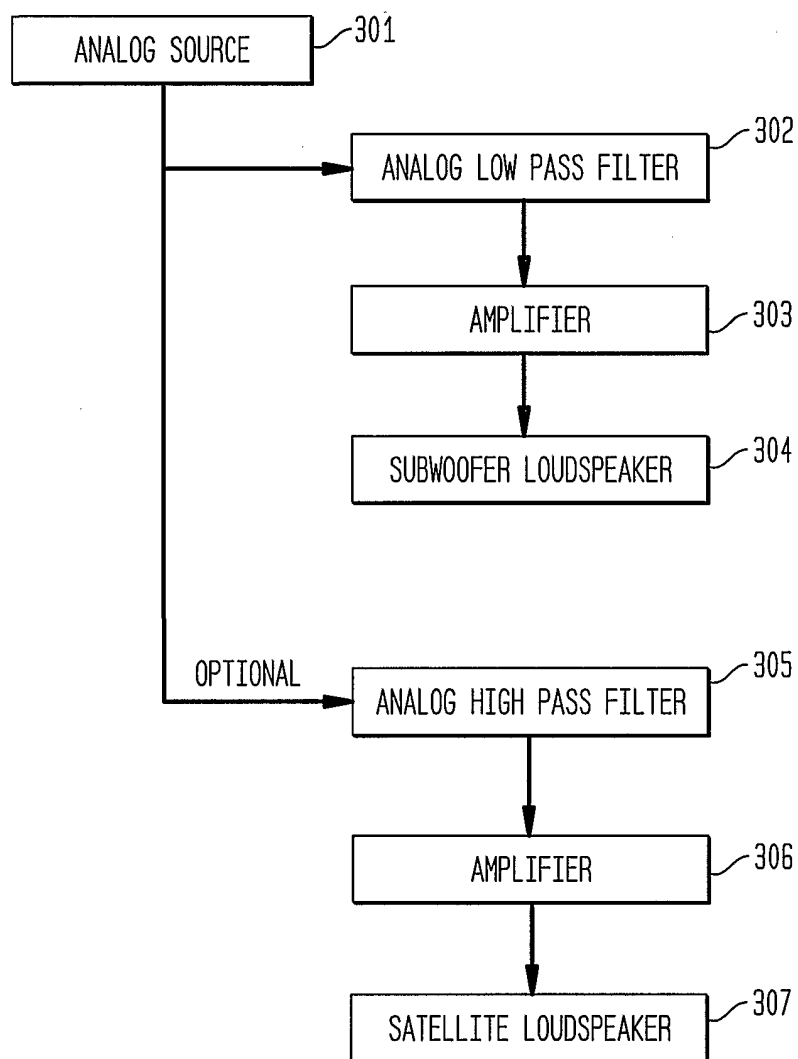
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FIG. 2



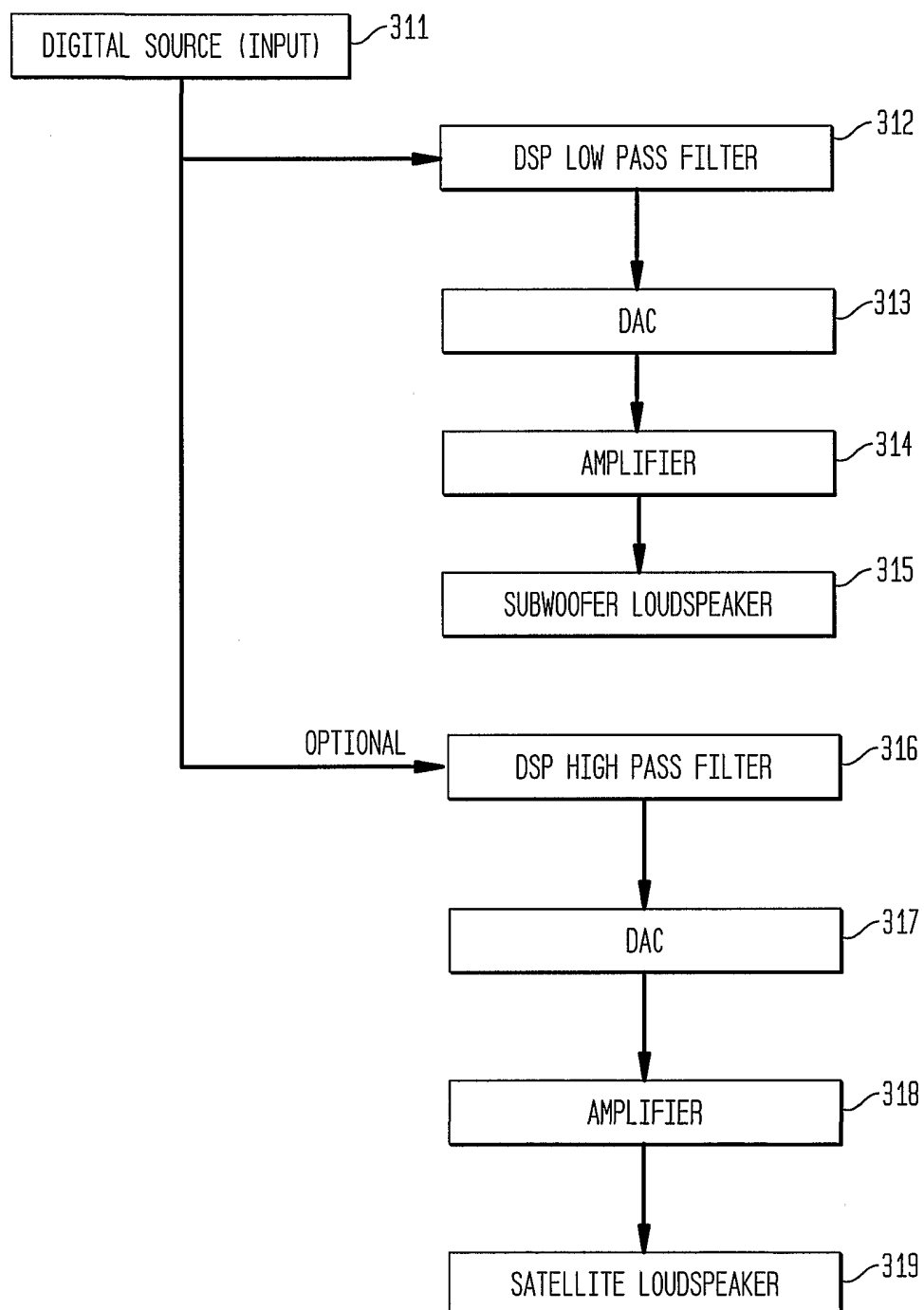
3/4

FIG. 3A



4/4

FIG. 3B



SUBSTITUTE SHEET (RULE 26)

International application No.

PCT/US00/13667

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H03G 5/00, 9/00, 5/00; H04B 3/20

US CL :381/98, 99, 100, 101, 102, 103, 66, 97

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 381/98, 99, 100, 101, 102, 103, 66, 97

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,325,435 A (DATE et al) 28 JUNE 1994, figs. 2-3.	1-30
A	US 5,361,381 A (SHORT) 01 November 1994, fig. 1A.	1-30

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

"	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

27 JUNE 2000

Date of mailing of the international search report

19 JUL 2000

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Facsimile No. (703) 305-3230

Authorized officer

MINSUN OH H. J. J. J.

Telephone No. (703) 308-6741

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