Electroacoustic System Realizations for the Linkwitz–Riley Crossover Networks*

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A design method is presented for the realization of the class of Linkwitz–Riley crossover networks for which the transfer function of the upper frequency driver is included as part of the transfer function of the high-pass network. The method is described in detail for a fourth-order crossover system, and techniques for its extension to higher order systems are given. A quasi-Linkwitz–Riley crossover network is defined which increases the order of the active filter for the high-pass network by 1 while approximately maintaining the desirable phase and amplitude characteristics of the Linkwitz–Riley network.

0 INTRODUCTION

Passive crossover network designs usually use the simplest crossover networks that will do the job. The design objective normally is a flat frequency response as measured "on axis." For the evaluation of the crossover between two drivers, "on axis" will be interpreted to imply that the measurements are made on a line perpendicular to the baffle containing the drivers and which bisects the line connecting their acoustic phase centers. If the measuring microphone is moved off this on-axis line, a differential phase delay will be introduced between the drivers and the measuring point, and the measured frequency response in the crossover region can deviate from that obtained on axis. In some loudspeaker specifications, "on axis" often implies on the tweeter axis. In this paper, however, it will be necessary to define it such that the distance between the acoustic centers of the drivers to the measuring point are equal.

One method that has been proposed to decrease the off-axis deviation in the crossover response between two drivers is to design the crossover networks so that the two drivers are in phase at the crossover frequency and so that the rates of change of the phase with frequency are the same for the two drivers. A class of crossover networks that satisfy this condition are called Linkwitz–Riley (L–R) or squared-Butterworth crossovers [1]. (Although not an author of the paper, R. Riley is given credit in [1] for suggesting that the cascade of two identical Butterworth filters meets the desired requirements.) The transfer functions for all of these networks have a sum or difference transfer function that is an all-pass transfer function. The lowest order transfer functions which satisfy the condition are second order, where the drivers are driven with opposite electrical phases. The next lowest order transfer functions are fourth order, where the drivers are driven in electrical phase.

Because fourth-order passive crossover networks are very complicated, especially when the effect of the nonresistive impedance of a voice coil is considered, a successful passive fourth-order realization could be difficult, if not impossible, to obtain in practice. However, with active filters the realization is simple for a biamplified (or triamplified, etc.) loudspeaker system.

The performance of the system is dependent on the crossover frequency (or frequencies). For example, in the crossover between a woofer and a midrange, the crossover frequency should be much higher than the lower cutoff frequency of both drivers. This minimizes the differential phase shift between the two drivers so that the desired phase at the crossover frequency would be set by the crossover networks alone and not by the drivers. For most midrange and tweeter drivers, however, the fundamental resonance of the diaphragm usually occurs at a frequency just below the typical crossover frequency. Because the lower cutoff frequency of a driver is approximately equal to its fundamental resonance frequency, it follows that it is difficult to use a crossover frequency that is too much higher than the midrange or tweeter cutoff frequency.

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Therefore the performance of a crossover network that satisfies the L–R condition can be perturbed by the differential phase shift between the drivers caused by the crossover frequency being too close to the lower cutoff frequency of one of the drivers. For example, if the crossover frequency is chosen to be equal to the fundamental resonance frequency of the midrange driver and this driver has a closed-box baffle, then the acoustic output of the midrange will lead that of the woofer by 90° at the crossover frequency. This phase lead will cause the same problems in the polar response of the system as are caused by crossover networks that are not of the L–R class. Therefore the system response does not have the unique property that the L–R networks are designed to provide.

This paper investigates the design of a crossover network system which satisfies the L–R condition, but the acoustical transfer function of the upper frequency driver is included in the overall transfer function ot the high-pass network. Because the phase response of this driver is part of the overall transfer function of the crossover system, the usual errors caused by neglecting it are minimized. The lowest order transfer function for which the design is possible is a fourth-order one. A complete solution is presented for this case. It is straightforward to extend the design method to higher order networks.

In addition to the L–R crossover system, a quasi-Linkwitz–Riley (q-L–R) crossover system is described which uses a fourth-order network on the lower frequency driver and a third-order network on the upper frequency driver. This crossover system is simpler than the strict L–R crossover but has similar performance.

Some background papers recommended for the interested reader are given in [2]–[6]. In [2] and [3] methods for designing crossover networks for correct system response are discussed. In [4] a method for incorporating the tweeter response into the crossover function is presented. In [5] a method for adjusting the resonance frequency and quality factor of a driver or system to obtain a desired response is discussed. In [6] the phase delay and the group delay of crossovers are discussed. In addition, a compensating network design is given which can be used in parallel with the voice coil of a driver to cause the input impedance of the parallel combination to simulate the dc resistance of the voice coil.

1 THE ELECTROACOUSTIC CROSSOVER SYSTEM

For simplicity, the development will assume a two-way loudspeaker system. The methods developed are applicable to higher way systems with minor modifications. Fig. 1 illustrates the diagram of such a system driven by two power amplifers which have active filter crossover networks preceding them. On axis between the two drivers, the acoustic pressure is equal to the sum of the pressures radiated by each driver. This sum can be written [7]

$$P_T = P_L + P_H = H_L(s)G_L(s) + H_H(s)G_H(s) \quad (1)$$

where $G_L(s)$ and $G_H(s)$ are the transfer functions from power amplifier input voltage to acoustic pressure output for the low-frequency driver and the high-frequency driver, respectively, and $H_L(s)$ and $H_H(s)$ are the transfer functions of the active crossover networks. The gain constants from v_i to P_L and from v_i to P_H depend on the gain of the two power amplifiers, the efficiency of the two drivers, and the distance between the observer and the baffle. In the following analysis it will be assumed that these two gain constants are equal to each other and that they have both been normalized to unity.

It will be assumed that each power amplifier has flat response in the audio band and that the acoustic medium does not modify the frequency response of the radiated pressure signal. In addition, it will be assumed that the crossover frequency between the two drivers is well below the upper cutoff frequency of each. Under these conditions, both $G_L(s)$ and $G_H(s)$ are high-pass transfer functions. In the case of a closed-box baffle, the order of the transfer functions is second [8]. For a vented-box baffle it is fourth [9]. It will be assumed that the lower cutoff frequency of the lower frequency driver is sufficiently low compared to the crossover frequency so that the phase of $G_L(j\omega)$ can be approximated by zero in the crossover region. This is a valid assumption in most systems because the lower cutoff frequency of a woofer is normally a factor of 10 or more lower than the crossover frequency. Under this assumption, the normalized total pressure for frequencies in the crossover region can be approximated by

$$P_T = H_L(s) + H_H(s)G_H(s) \; . \quad (2)$$

Almost without exception, midrange and tweeter drivers have an integral closed-box baffle as part of their construction. Therefore it will be assumed that $G_H(s)$ is a second-order transfer function having the normalized form [8]

$$G_H(s) = \frac{(s/\omega_C)^2}{(s/\omega_C)^2 + (1/Q_{TC})(s/\omega_C) + 1} \quad (3)$$

where ω_C is the system resonance frequency and Q_{TC} is the total quality factor. In order for the normalized

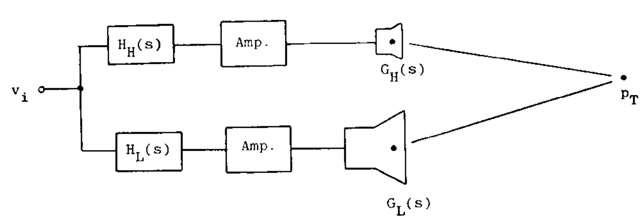

Fig. 1. Two-way loudspeaker system for which total acoustic pressure P_T radiated is measured on axis. Transfer functions $H_L(s)$ and $H_H(s)$ are those of active crossover networks; transfer functions $G_L(s)$ and $G_H(s)$ are the transfer functions from driver input voltage to output pressure at the measuring point.

total pressure to satisfy the L–R condition for a fourth-order transfer function, it follows that $H_L(s)$ and $H_H(s)G_H(s)$ of Eq. (2) must be given by [1]

$$H_L(s) = \left[\frac{1}{(s/\omega_0)^2 + \sqrt{2}(s/\omega_0) + 1}\right]^2 \quad (4)$$

$$H_H(s)G_H(s) = \left[\frac{(s/\omega_0)^2}{(s/\omega_0)^2 + \sqrt{2}(s/\omega_0) + 1}\right]^2 \quad (5)$$

where ω_0 is the crossover frequency.

Comparison of Eqs. (3) and (5) shows that if $\omega_C = \omega_0$ and $Q_{TC} = 1/\sqrt{2}$, then one of the factors on the right-hand side of Eq. (5) can be assigned to $H_H(s)$ and the other to $G_H(s)$. Therefore it follows that if the transfer function of the upper frequency driver is Butterworth ($Q_{TC} = 1/\sqrt{2}$) and the crossover frequency is chosen to be equal to the fundamental resonance frequency of this driver, then the product $H_H(s)G_H(s)$ will be the transfer function of the high-pass L–R function for a fourth-order crossover network. However, the active filter which precedes the power amplifier that drives the upper frequency driver is only of second order.

The choice of a crossover frequency that is equal to the fundamental resonance frequency of an upper frequency driver is a condition that can be met easily. Any properly designed system will have $\omega_0 \geqslant \omega_C$. In some cases, however, ω_C may be so low that the power handling of the upper frequency driver may be affected if the crossover frequency ω_0 is chosen that low. Therefore, a desirable design alternative is to have $\omega_0 > \omega_C$. In addition, most midrange and tweeter drivers are mounted in a fixed-volume closed-box baffle so that the total quality factor of the upper frequency driver may not be $1/\sqrt{2}$. In this case the second condition on the realization of the crossover system cannot be met. To modify the design to account for these conditions, a second-order biquad filter may be used as part of $H_H(s)$ to electrically alter the "effective" fundamental resonance frequency and quality factor of this driver. The transfer function for this biquad would be given by

$$T(s) = \frac{\omega_C^2}{\omega_0^2}\,\frac{(s/\omega_C)^2 + (1/Q_{TC})(s/\omega_C) + 1}{(s/\omega_0)^2 + \sqrt{2}(s/\omega_0) + 1} \, . \quad (6)$$

For most drivers Q_{TC} would probably be greater than $1/\sqrt{2}$ so that the biquad filter would have a "dipping response" at $\omega = \omega_C$. A possible active realization for $H_L(s)$ and $H_H(s)$ that includes the biquad filter is shown in Fig. 2.

In Fig. 2(a) operational amplifiers A1 and A2 form a fourth-order cascade infinite-gain multiple-feedback low-pass filter [10]. In order for this filter to have the required transfer function as given in Eq. (4), the following equations must hold:

$$R_{a1} = R_{a2} = R_{a3} = \frac{1}{\omega_0\sqrt{C_{a1}C_{a2}}} \quad (7)$$

$$C_{a1} = 4.5C_{a2} \, . \quad (8)$$

In Fig. 2(b) operational amplifiers A3 through A6 form a second-order biquad filter [11] which realizes the transfer function of Eq. (6). Operational amplifier A7 forms a second-order infinite-gain multiple-feedback high-pass filter [10]. The design equations for these filters are

$$\sqrt{2}R_{b1} = R_{b3} = \left(\sqrt{2} - \frac{1}{Q_{TC}}\frac{\omega_C}{\omega_0}\right)R_{b4} = R_{b5} = R_{b6} = \frac{1}{\omega_0 C_{b1}} \quad (9)$$

$$R_{b2} = \frac{1}{\omega_0 C_{b2}} \quad (10)$$

$$R_{b7} = \frac{\omega_0^2 - \omega_C^2}{\omega_0\left|\sqrt{2}\omega_0 - \omega_C/Q_{TC}\right|}R_{b8} = R_{b9} = R_{b10} \quad (11)$$

$$C_{b3} = C_{b4} = C_{b5} = \frac{1}{\omega_0\sqrt{R_{b11}R_{b12}}} \quad (12)$$

$$4.5R_{b11} = R_{b12} \quad (13)$$

where the biquad design formulas are valid only for $\omega_0 \geqslant \omega_C$. Connection A in the biquad is used if $\sqrt{2}Q_{TC}\omega_0/\omega_C > 1$. Connection B is used if $\sqrt{2}Q_{TC}\omega_0/\omega_C < 1$. In the event that $\sqrt{2}Q_{TC}\omega_0 = \omega_C$, then connection A is used and the equations for R_{b4}, R_{b7}, and R_{b8} are modified as follows:

$$R_{b4} = \frac{\omega_0}{(\omega_0^2 - \omega_C^2)C_{b1}} \quad (14)$$

$$R_{b7} = \text{open circuit} \quad (15)$$

$$R_{b8} = R_{b10} \, . \quad (16)$$

The next higher order transfer functions which satisfy the L–R condition are sixth. In this case $H_L(s)$ and $H_H(s)G_H(s)$ are given by

$$H_L(s) = \left\{\frac{1}{[(s/\omega_0)^2 + s/\omega_0 + 1][s/\omega_0 + 1]}\right\}^2 \quad (17)$$

$$H_H(s)G_H(s) = \left\{\frac{(s/\omega_0)^3}{[(s/\omega_0)^2 + s/\omega_0 + 1][s/\omega_0 + 1]}\right\}^2 \, . \quad (18)$$

If the crossover frequency ω_0 is chosen to be equal to the fundamental resonance frequency ω_C of the upper frequency driver, it is obvious from Eq. (18) that there are two choices for $G_H(s)$. One would have $Q_{TC} = ½$ and the other would have $Q_{TC} = 1$. The order of the crossover network for the upper frequency driver would be fourth. As with the fourth-order system described in the preceding, a biquad filter could be used with the sixth-order system to electrically alter the "effective" fundamental resonance frequency and quality factor of the upper frequency driver so that arbitrary quality factors could be accommodated and a crossover frequency greater than ω_C could be used. The design of the filters would be similar to those given in Fig. 2 and will not be presented here. The next higher order transfer functions which satisfy the L–R condition are eighth. It is straightforward to extend the design methods presented here to this case and to higher orders.

2 A QUASI-LINKWITZ–RILEY CROSSOVER SYSTEM

The method for crossover system design presented in the preceding section always results in a network for the upper frequency driver that has an order of 2 less than the network for the lower frequency driver. In addition, the network for the upper frequency driver includes a biquad filter which complicates its design. In the case of the fourth-order crossover system, the high-pass crossover network has an order of 2. For a high-power system this may not be sufficient to provide protection of the upper frequency driver, so that the more complicated sixth-order system would have to be used. This would give a fourth-order filter for the high-pass network.

In this section an alternate crossover is presented which uses the fourth-order network on the lower frequency driver but a third-order network on the upper frequency driver. In addition, the biquad filter is not used. Although the crossover does not meet the L–R condition in the strictest sense, it can come very close. Because the transfer function of the upper frequency driver is accounted for in the design, the overall electroacoustic performance can be better than a strict L–R crossover that does not take into account the transfer function of this driver.

At the crossover frequency, there are two desirable conditions that the crossover networks of an L–R crossover satisfies. If the gain constant of each network is normalized to unity, these conditions are: 1) each output should have the same phase with an amplitude of 0.5 and 2) the rate of change of the phase with frequency, that is, the group delay, should be the same for the two networks. Suppose that it is desired to use a fourth-order network on the lower frequency driver and a third-order network on the upper frequency driver. Let the crossover network transfer function for the lower frequency driver be given by Eq. (4). At $s = j\omega_0$, this transfer function has a magnitude of 0.5 and a phase

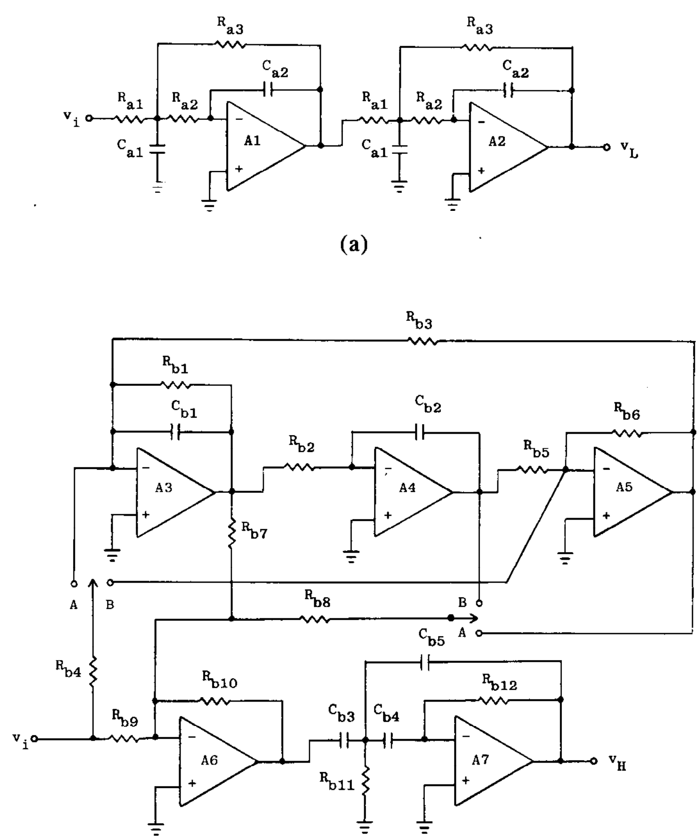

Fig. 2. (a) Operational amplifier realization of low-pass filter for fourth-order crossover system. (b) Operational amplifier realization of high-pass filter for fourth-order system including biquad for electrically modifying the "effective" fundamental resonance frequency and total quality factor of upper frequency driver. Switch connections are explained in text.

of $-180°$. Let the transfer function of the crossover network for the upper frequency driver be given by

$$H_H(s) = \frac{(s/\omega_0)^3}{[s/\omega_0 + 1][(s/\omega_0)^2 + \sqrt{2}(s/\omega_0) + 1]} . \quad (19)$$

At $s = j\omega_0$, this transfer function has a magnitude of 0.5 and a phase of $+135°$. It follows that if the crossover frequency ω_0 is chosen to be a frequency at which the phase of $G_H(j\omega_0)$ is $+45°$, then the product $H_H(j\omega_0)\ G_H(j\omega_0)$ would have a phase of $+180°$. If $|G(j\omega_0)| \cong 1$, then condition 1) given above as applied to $H_L(j\omega_0)$ and $H_H(j\omega_0)G_H(j\omega_0)$ would be satisfied. These conditions can be closely met with many midrange and tweeter drivers.

Condition 2) on the rate of change of the phase of $H_L(j\omega)$ and $H_H(j\omega)G_H(j\omega)$ is not so obvious. To investigate this, let β_L be the phase of $H_L(j\omega)$ in Eq. (4), let β_{H1} be the phase of $G_H(j\omega)$ in Eq. (3), and let β_{H2} be the phase of $H_H(j\omega)$ in Eq. (19). At $\omega = \omega_0 = 2\pi f_0$ it can be shown that the rates of change of these three phases with respect to frequency are given by

$$\frac{d\beta_L}{df_0} = \frac{-360\sqrt{2}}{\pi f_0} \quad \text{[deg/Hz]} \quad (20)$$

$$\frac{d\beta_{H1}}{df_0} = \frac{-180k}{\pi Q_{TC} f_0} \frac{1 + k^2}{(1 - k^2)^2 + k^2/Q_{TC}^2} \quad \text{[deg/Hz]} \quad (21)$$

$$\frac{d\beta_{H2}}{df_0} = \frac{-90(1 + 2\sqrt{2})}{\pi f_0} \quad \text{[deg/Hz]} \quad (22)$$

where $k = \omega_0/\omega_C = f_0/f_C$. Condition 2) on the rate of change of the phase at the crossover frequency can be written

$$\frac{d\beta_L}{df_0} = \frac{d\beta_{H1}}{df_0} + \frac{d\beta_{H2}}{df_0} . \quad (23)$$

For any f_0 the values of k and Q for which the phase angle of $G_H(j\omega)$ is 45° and for which Eq. (23) holds are given by

$$k = 1.85 \quad (24)$$

$$Q_{TC} = 0.765 . \quad (25)$$

It thus follows that if the upper frequency driver has a total quality factor of 0.765 and the crossover frequency is a factor of 1.85 above its fundamental resonance frequency, then the condition on the total phase and on the rate of change of the phase, that is, the group delay, will be satisfied at the crossover frequency. A total quality factor of 0.765 is certainly within the range of values covered by most midrange and tweeter drivers (if at the lower end of it). Therefore the condition on Q_{TC} could be approximately satisfied by most drivers. A factor of 1.85 for ω_0/ω_C puts the crossover frequency approximately one octave above the resonance frequency for the upper frequency driver. This in combination with a third-order crossover network that is 6 dB down at the crossover frequency would certainly qualify as a good candidate for the high-pass crossover in a high-power system.

Fig. 3 shows an active realization of the third-order high-pass filter given in Eq. (19) for the q-L–R crossover. The associated low-pass filter is the same as that given in Fig. 2(a). The design equations for the high-pass filter are

$$1.37R_{c1} = 0.348R_{c2} = 2.10R_{c3} = \frac{1}{\omega_0 C_{c1}} \quad (26)$$

$$C_{c1} = C_{c2} = C_{c3} . \quad (27)$$

To investigate the performance of the q-L–R crossover, a computer simulation with the PSPICE electrical circuit simulator software was performed. The element values for the low-pass and high-pass filters of Figs. 2(a) and 3, respectively, were calculated for a normalized crossover frequency of $f_0 = 1$ Hz. To complete the simulation, an active second-order high-pass filter was included in cascade with the high-pass section to simulate the transfer function of the upper frequency driver. This transfer function had a normalized resonance frequency of $f_C = 1/1.85$ Hz and a quality factor of $Q_{TC} = 0.765$.

Fig. 4 shows the magnitude plots of the output of the low-pass filter, the output of the high-pass filter, and the sum of the two outputs. It can be seen that the sum exhibits a magnitude that ripples slightly through the crossover region. The strict L–R crossover system discussed in the previous section would not exhibit this ripple.

Fig. 5 shows the simulated phase responses of the low-pass filter and the high-pass filter in cascade with the filter used to simulate the upper frequency driver. It can be seen that the two phase functions exhibit very close agreement in and above the crossover region. Thus the conditions that the two outputs have the same phase delay and the same group delay in the crossover region are satisfied. Below the crossover region, the two functions diverge. The strict L–R crossover system described in the preceding would not exhibit this divergence. The phase plots in the figure are shown modulo−360°. Thus the apparent jump discontinuities near 1.0 Hz are not real discontinuities because the phases

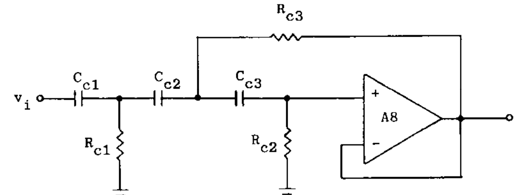

Fig. 3. Operational amplifier realization of third-order high-pass filter for quasi-Linkwitz–Riley crossover system.

−180° and +180° are the same.

It is to be noted that, below the crossover frequency, the wavelength of the radiated sound increases as frequency is decreased so that the separation in wavelengths between the acoustic phase centers of the lower and upper frequency drivers decreases. This minimizes any off-axis deviation in the pressure response of the system caused by the divergence in the two phase functions.

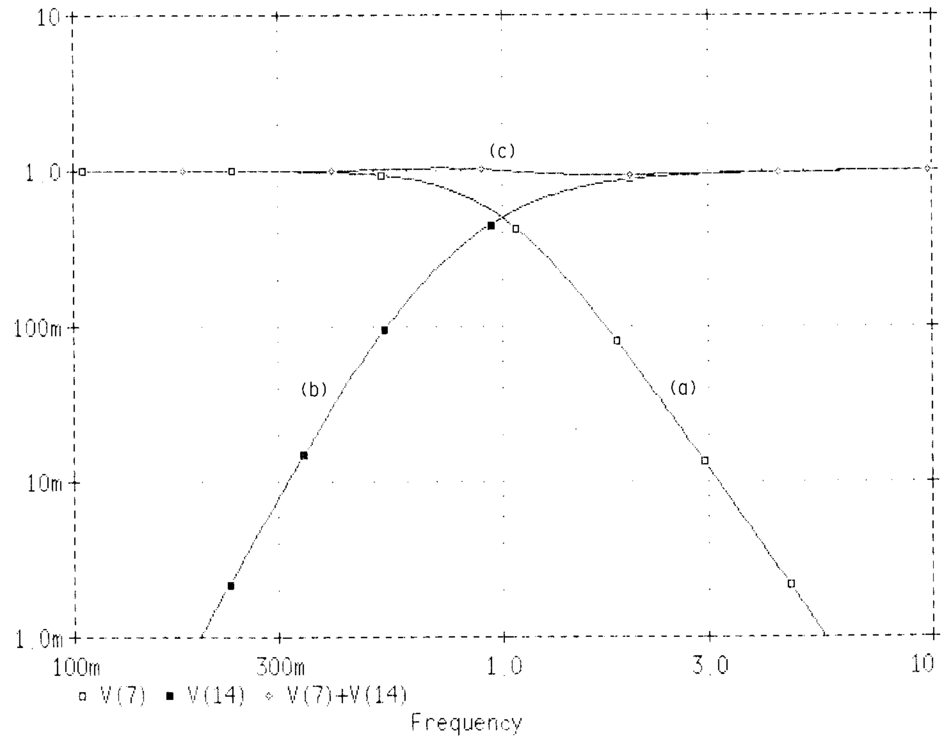

Fig. 4. Computer simulation of the magnitude of pressure outputs of (a) lower frequency driver, V(7), (b) upper frequency driver, V(14), and (c) sum of the two, V(7) + V(14), for quasi-Linkwitz–Riley crossover system. Crossover frequency is normalized to 1 Hz. Horizontal axis—frequency in hertz from 0.1 Hz (100m) to 10 Hz; vertical axis—normalized gain from 0.001 (1.0m) to 10.

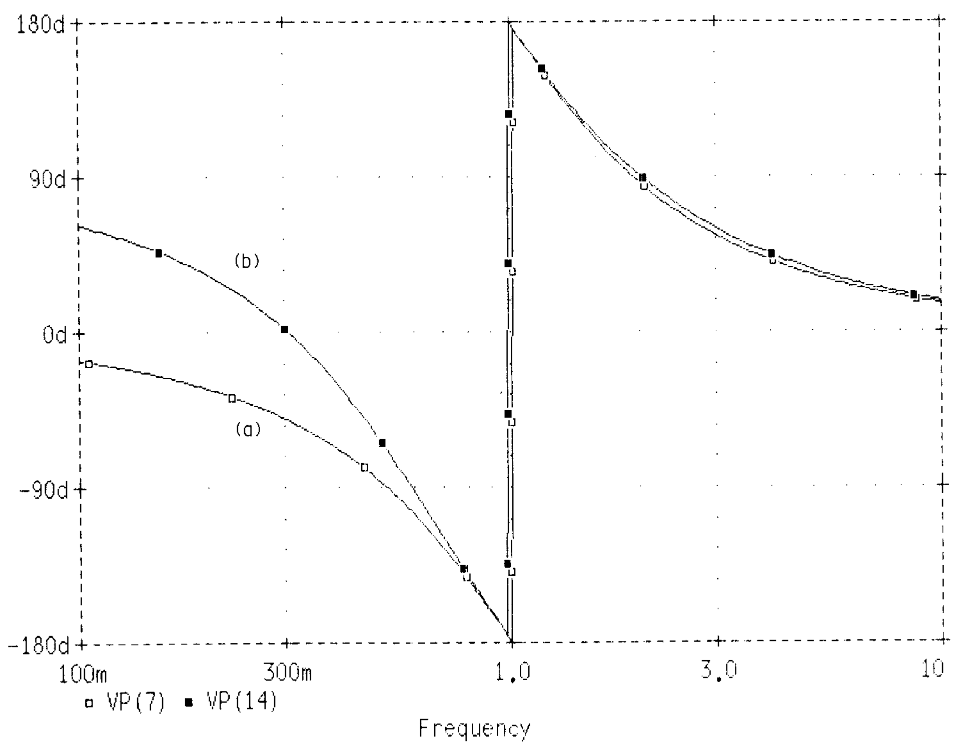

Fig. 5. Computer simulation of the phase of outputs of (a) lower frequency driver, VP(7), and (b) upper frequency driver, VP(14), for quasi-Linkwitz–Riley crossover system. Crossover frequency is normalized to 1 Hz. Horizontal axis—frequency in hertz from 0.1 Hz (100m) to 10 Hz; vertical axis—phase in degrees from −180° (−180d) to +180° (180d). See text for discussion of apparent discontinuities near 1.0 Hz.

Therefore the divergence occurs on the preferred side of the crossover frequency, that is, on the lower side.

If the upper frequency driver does not have the required value of Q_{TC}, the performance of the q-L–R system will be perturbed. To investigate this, let $A_L = |H_L(j\omega_0)|$, $A_H = |G_H(j\omega_0)H_H(j\omega_0)|$, and $\beta_H = \beta_{H1}(\omega_0) + \beta_{H2}(\omega_0)$. For $Q_{TC} = 0.765$ it can be shown that $\Delta A_H/A_H = 0.5\Delta Q_{TC}/Q_{TC}$ and $\Delta\beta_H/\beta_H = (1/2\pi)\,\Delta Q_{TC}/Q_{TC}$. If the phase and amplitude errors can be considered independently, it follows that a 20% increase in Q_{TC} will cause a 0.83-dB increase in the sum $A_L + A_H$ and a 1.8° decrease in β_H. At the crossover frequency, therefore, it can be concluded that the q-L–R system is fairly insensitive to changes in Q_{TC} about the required value of 0.765.

To determine the difference in the performance of the q-L–R network and an L–R crossover network which does not take into account the phase response of the driver, a second computer simulation was performed. A fourth-order crossover network was used on both the lower frequency driver and the upper frequency driver. Again it was assumed that the upper frequency driver could be modeled as a driver in a closed-box baffle having a resonance frequency a factor of 1.85 below the crossover frequency and with a total quality factor of 0.765. Fig. 6 shows the magnitude plots of the output from the low-pass filter, the output of the high-pass filter in cascade with the network used to simulate the upper frequency driver, and the sum of the two outputs. As with the q-L–R system, the sum exhibits a magnitude that ripples slightly (though less than in Fig. 4) through the crossover region. The strict L–R crossover system discussed in the previous section would not exhibit this ripple.

Fig. 7 shows the simulated phase responses of the low-pass filter and the high-pass filter in cascade with the filter used to simulate the upper frequency driver. It can be seen that the two phase functions do not exhibit the same slope at the crossover frequency. Thus one of the key features of the L–R functions is not maintained. Below the crossover region, the two functions diverge by approximately twice as much as for the q-L–R system. It can be concluded that the third-order high-pass filter network comes much closer to producing the desirable phase characteristics of the L–R functions when the transfer function of the upper frequency driver is taken into account. The comment made with reference to Fig. 5 concerning the apparent discontinuities in the phase plots near 1.0 Hz applies to Fig. 7.

The reader is cautioned that general conclusions based on the plots presented in Figs. 4–7 may not be valid for a driver which has a Q_{TC} that differs significantly from 0.765 or if the ratio of the crossover frequency to the resonance frequency of the upper frequency driver differs from 1.85.

3 CONCLUSIONS

With active filter techniques it is possible to design the crossover networks for a multiway loudspeaker system such that the transfer functions of the upper frequency drivers are incorporated into the crossover network design in such a way that the system response, as opposed to the response of the crossover networks

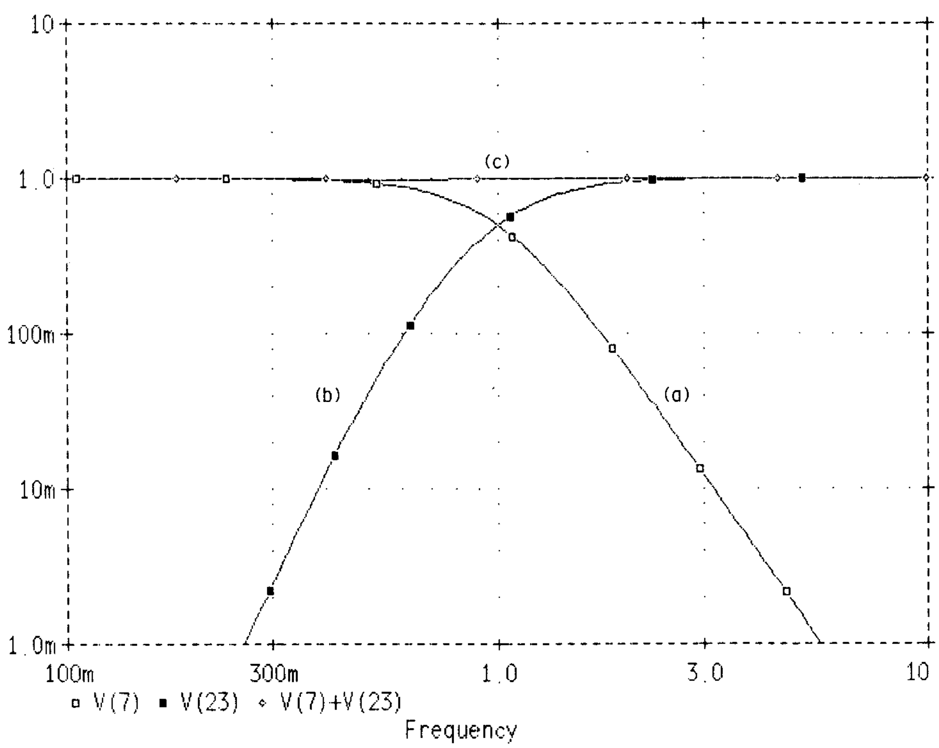

Fig. 6. Computer simulation of the magnitude of pressure outputs of (a) lower frequency driver, V(7), (b) upper frequency driver, V(23), and (c) sum of the two, V(7) + V(23), with fourth-order Linkwitz-Riley crossover networks. Crossover frequency is normalized to 1 Hz. Horizontal axis—frequency in hertz from 0.1 Hz (100m) to 10 Hz; vertical axis—normalized gain from 0.001 (1.0m) to 10.

alone, meets the conditions of the L–R class of crossover networks. The conventional L–R networks require the same order transfer functions for the low-pass and the high-pass sections. For the design presented here, the order of the high-pass section is 2 less than that of the low-pass section. In the general case, however, the high-pass network must be in cascade with a biquad filter which serves the function to electrically modify the effective transfer function of the upper frequency driver.

In the crossover region it is possible to closely approximate the phase characteristics of the fourth-order L–R crossover networks with a system design that uses a fourth-order low-pass network on the lower frequency driver and a third-order high-pass network without the biquad filter on the upper frequency driver.

4 ACKNOWLEDGMENT

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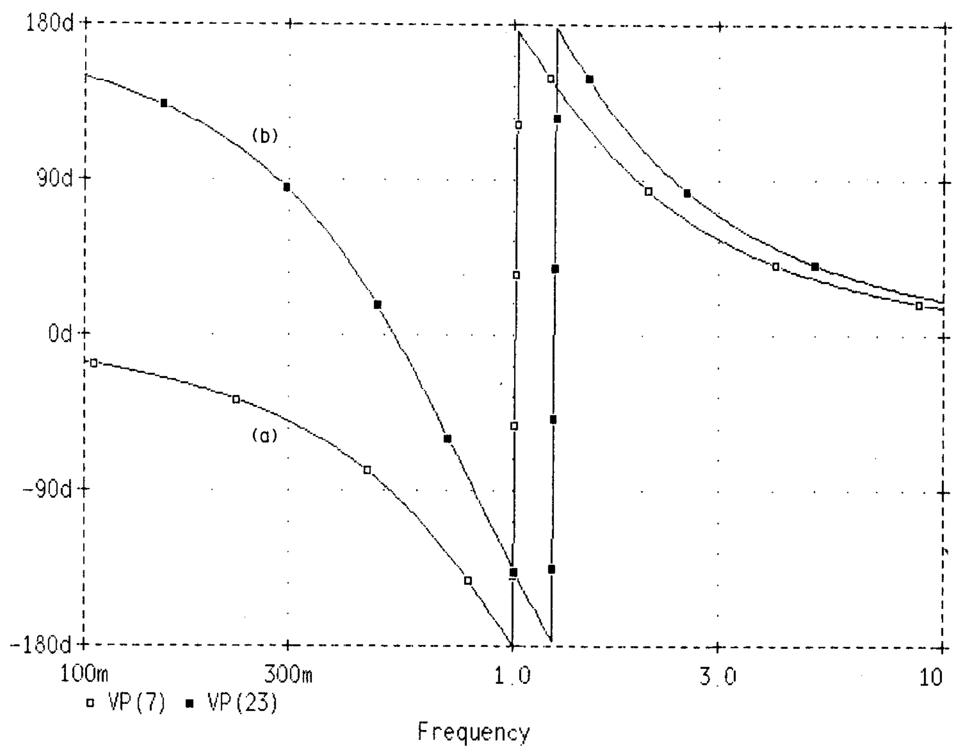

Fig. 7. Computer simulation of the phase of outputs of (a) lower frequency driver, VP(7), and (b) upper frequency driver, VP(23), with fourth-order Linkwitz–Riley crossover networks. Crossover frequency is normalized to 1 Hz. Horizontal axis—frequency in hertz from 0.1 Hz (100m) to 10 Hz; vertical axis—phase in degrees from −180° (−180d) to +180° (180d). See text for discussion of apparent discontinuities near 1.0 Hz.