A New Set of Sixth-Order Vented-Box Loudspeaker System Alignments*

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A new and useful set of low-frequency assisted alignments contain Thiele's sixth-order Butterworth (B_6) alignment as a central member. The new alignments provide the same low cutoff with moderate amplifier boost (+6 dB) and low out-of-band driver excursion as the assisted B_6 alignment 15 of Thiele. The method of alignment generation is based on shifts of driver suspension compliance.

INTRODUCTION: Thiele, in his monumental work on vented-box loudspeaker systems [1], describes several classes of sixth-order high-pass vented-system alignments which require the use of auxiliary second-order high-pass filters as part of their concept. His B_6 class I alignment 15 is found to be one of the most useful and attractive for providing low cutoff with moderate amplifier lift and low out-of-band driver cone excursion. Unfortunately, this particular alignment is available only to those who can control driver suspension compliance to suit their needs or have drivers whose resonance frequencies happen to coincide precisely with the desired cutoff frequency (f_3, −3 dB). Thiele's filter-function derived C_6 alignments 16 to 19 [1, Part 1] appear to allow other choices of driver compliance (or resonance), but Thiele himself recommends that these be avoided (particularly alignments 17 to 19) because of large amounts of low-frequency boost which occur at frequencies significantly below that of box resonance.

The relative insensitivity of vented-box frequency response and cutoff frequency to changes in the driver's suspension compliance as noted in [1, p. 398], [2, p. 553], and [3, p. 254] suggested to the writer a new method of alignment generation. This method is used here to generate a series of alignments, based on the Thiele B_6 alignment 15, which possess all the basic advantages of that alignment but allow a wide choice of driver compliance. All the new alignments have coincident cutoff, box resonance, and maximum boost frequencies and use the same modest amount of lift (+6 dB at 1.07 times cutoff frequency). They also exhibit the same high efficiency constant [4]–[6] and ability to control subsonic cone excursions as the Thiele B_6 alignment. It must be stressed that the alignments were generated by changing driver compliance only; the driver moving mass remains constant.

In a recent paper [7] Thiele further describes the advantages of higher order assisted alignments in providing maximum useful acoustic output with minimum cone excursion both in and out of the system's passband. He also emphasizes the desirability of locating the box resonance frequency at the cutoff frequency.

THEORY

Rather large changes in driver suspension compliance can be tolerated before any significant change occurs in the

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frequency response and cutoff frequency f_3 of a vented-box system.

The functional dependence of the Thiele driver parameters on the fundamental driver physical parameters are given in [3, eqs. (8)–(10)]. Considering only the dependence on driver suspension compliance C_{MS}, the following proportionalities show how the Thiele vented-box system parameters depend on C_{MS}:

$$h \propto \sqrt{C_{MS}} \quad (1)$$

$$Q_T \propto 1/\sqrt{C_{MS}} \quad (2)$$

$$\alpha \propto C_{MS} \quad (3)$$

where h ratio of box-to-driver resonance frequencies $(=f_B/f_S)$,
Q_T total effective Q of the driver at f_S, considering both mechanical and electrical losses,
α ratio of driver compliance equivalent volume to effective box volume $(= V_{AS}/V_B)$.

Eq. (2) is an approximation which is derived by assuming no driver mechanical losses and an amplifier source impedance of zero. Eqs. (1)–(3) show how a possible change in C_{MS} can cause a subsequent realignment of the Thiele system parameters. This specific type of realignment does not, however, affect the response of the vented-box system to any great degree.

If a normalized compliance value designated C_N is the ratio of actual compliance to correct compliance C_{MS}/C'_{MS} for a specific alignment, the following system parameter generator set can be defined, where the primed variables indicate original system values:

$$h = h' \sqrt{C_N} \quad (4)$$

$$Q_T = Q_T' / \sqrt{C_N} \quad (5)$$

$$\alpha = \alpha' C_N. \quad (6)$$

Eqs. (4)–(6) can be used to generate a new series of alignments around any specific arbitrary alignment by assigning specific values to C_N.

RESULTS

If the auxiliary filter-assisted B_6 Thiele alignment 15 is chosen as the alignment for compliance perturbation ($h' = 1$, $Q_T' = 0.299$, and $\alpha' = 2.73$), a unique set of assisted alignments is produced. Table I shows the resultant generated alignments.

In Table I the maximum compliance shift is limited to a factor of four above and below the correct value. Intermediate alignments are chosen so as to raise f_3/f_S by $1/6$ octave steps over the range of 0.5 to 2. The reader will note that in every case h, f_3/f_S, and f_{aux}/f_S all occur at the same normalized frequency, while the response shape and resultant peak boost (+6 dB) of the auxiliary filter does not change.

Fig. 1 shows several responses for these alignments. The maximum response deviation occurs for the lowest normalized compliance alignments, $C_N < 0.5$. For the $C_N = 0.25$ alignment, the maximum ripple error is about 2.5 dB over the range of f_3 to $2f_3$. The response for the low C_N alignments may be flattened by a slight increase in box volume and/or adjustment of auxiliary filter boost amplitude.

It must be stressed that these alignments represent only discrete selections from a continuum of possible alignments. Interpolating between values on Table I or reapplication of Eqs. (4) to (6) can be accomplished to yield intermediate values.

Combining Eqs. (4) to (6) and noting that $h' = 1$, $Q_T' \approx 0.3$ and $\alpha' \approx 2.7$ yields

$$f_B = f_3 = f_{aux} \approx 0.3 \frac{f_S}{Q_T} \quad (7)$$

$$V_B \approx 4.1 Q_T^2 V_{AS}. \quad (8)$$

Table I. New vented-box sixth-order assisted alignments.

Normalized Compliance	Box Design				Auxiliary Filter (Q_{aux}=1.93, Peak Lift=6 dB)	
C_N	h f_3/f_s	α	$1/\alpha$	Q_T	f_{aux}/f_S	f_{pk}/f_S
4.000	2.000	10.92	0.0915	0.150	2.000	2.140
3.175	1.782	8.67	0.115	0.168	1.782	1.907
2.520	1.587	6.88	0.145	0.188	1.587	1.699
2.000	1.414	5.46	0.183	0.211	1.414	1.513
1.587	1.260	4.33	0.231	0.237	1.260	1.348
1.260	1.122	3.44	0.290	0.266	1.122	1.201
1.000*	1.000	2.73	0.366	0.299	1.000	1.070
0.794	0.891	2.17	0.461	0.336	0.891	0.953
0.630	0.794	1.72	0.581	0.377	0.794	0.849
0.500	0.707	1.36	0.732	0.423	0.707	0.757
0.397	0.630	1.08	0.922	0.475	0.630	0.674
0.315	0.561	.86	1.162	0.533	0.561	0.600
0.250	0.500	.68	1.464	0.598	0.500	0.535

Transfer function of auxiliary filter $= s^2/[s^2 + (2\pi f_{aux}/Q_{aux}) s + (2\pi f_{aux})^2]$. f_{pk} = frequency at which peak lift occurs for auxiliary filter.
* Thiele's alignment 15.

Eqs. (7) and (8) may be used instead of Table I for system design using a hand calculator. Application of relations (7) and (8) to a specific driver very quickly indicates whether it will be suitable for a particular application.

Eq. (7) emphasizes the fact that it is not the driver resonance frequency which is important, but the quantity f_S/Q_T which indicates how low a driver will go. Note that f_S/Q_T is independent of driver suspension compliance and depends only on driver moving mass, motor strength (*BL* product), and voice coil resistance.

Assuming a desired cutoff in the range $25 \leq f_3 \leq 50$ Hz, Eq. (7) indicates that the resonance divided by Q (f_S/Q_T) can range from roughly 80 to 160 Hz. Any driver having this ratio of f_S to Q_T would be a likely candidate for use in the sixth-order alignments. If a hump of up to 3 dB is acceptable, Q_T values up to 0.85 would be usable.

APPLICATION

The described sixth-order vented-box alignments are very useful when applied to two widely different classes of drivers:

Class I, the high-compliance long-throw low-resonance low-Q_T driver such as found in the typical closed box (acoustic suspension) speaker systems;

Class II, the low-compliance short-throw high-resonance high-Q_T driver that one normally associates with moderately inexpensive drivers.

The class I driver used in a vented-box system is found to fit the quasi third-order Butterworth alignments of Thiele (QB_3, alignments 1 to 4) [1]. Unfortunately the QB_3 alignments have low input power handling capabilities below box resonance because of the driver's high compliance. Ashley says, "The QB_3 alignments are okay until you watch the cone and see turntable rumble you wouldn't believe" [8]. Thiele tells us that the solution to this problem lies in using an assisted higher order alignment which uses a high-pass auxiliary filter [7]. The new alignments described in this paper ($C_N > 1$) are well suited for this application. Appendix I describes a sixth-order vented system designed around a typical class I driver. Comparative curves are included on the same driver when used in the closed-box and vented-QB_3 configurations. The assisted configuration is found to extend the low-frequency cutoff down more than an octave below that provided by a closed-box system using the same driver.

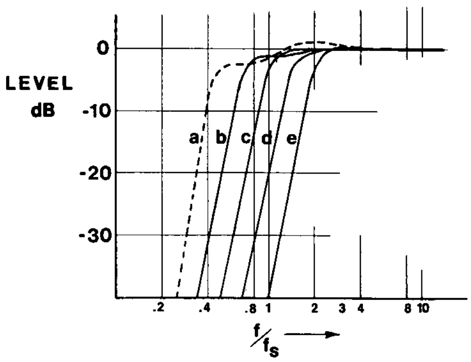

Fig. 1. Selected low-frequency responses from new set of sixth-order assisted vented-box alignments. The frequency axis is normalized to the driver's free-air resonance frequency f_S. *a*—$C_N = 0.25$, $f_3 = 0.5 f_S$; *b*—$C_N = 0.5$, $f_3 = 0.707 f_S$; *c*—$C_N = 1$, $f_3 = f_S$ (Thiele's alignment 15); *d*—$C_N = 2$, $f_3 = 1.414 f_S$; *e*—$C_N = 4$, $f_3 = 2 f_S$.

The class II driver is at an immediate disadvantage because of its high resonance and low displacement capabilities. Use of the new sixth-order vented-box alignments ($C_N < 1$) allows the designer to "milk" more usable low-frequency output out of this type of driver than any other system configuration. Appendix II describes a sixth-order system design using a typical class II driver which has usable response down to an octave below the driver's free-air resonance. The relatively low box tuning of the sixth-order system enables it to handle full thermal rated input power down to a much lower frequency than the closed-box configuration.

An examination of Table I reveals that the α and Q_T values for the $C_N = 0.5$ alignment are approximately those required for the vented-box unassisted fourth-order Butterworth (B_4) alignment 5 of Thiele ($\alpha = 1.414$ and $Q_T = 0.383$). Practically speaking this means that a system which is initially aligned to a B_4 response may be turned into a pseudo-B_6 alignment simply by retuning the box one half octave lower and adding the correct auxiliary equalization filter. The net effect on the system response is a one-half octave extension of low-frequency response with only about 3 dB less maximum acoustic power output capability in the passband. The addition of the auxiliary high-pass filter also greatly reduces the vented system's susceptibility to below passband subsonic signals such as turntable rumble, record warp, etc.

An adaptation of this B_4 to B_6 response shift is commercially available in a monitor loudspeaker system. The vented-box low end of this system as originally designed is a B_4 high-pass response with an f_3 of 40 Hz (Fig. 2, curve *a*, driver and system parameters are listed in Appendix IV). For those situations where a lower cutoff frequency is desired (for electronic synthesizer or pipe organ monitoring, for example), a "stepdown" kit is available which includes an equalizer and a vent modification assembly to shift f_3 to 28 Hz (Fig. 2, curve *b*). The vent modification assembly shifts the box tuning frequency f_B from 40 Hz down to 28 Hz (Fig. 3, curve *a*), while the underdamped second-order high-pass filter provides a modest 6-dB peak boost at 30 Hz (Fig. 3, curve *b*) to return the response back to a roughly flat condition as shown in Fig. 2, curve *b*. This

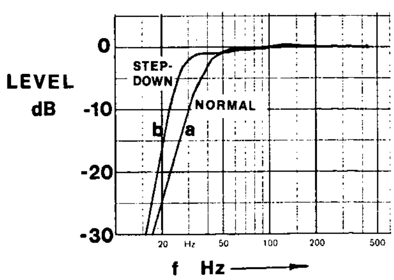

Fig. 2. Display of low-frequency responses for the 380-mm (15-in) driver vented-box system. *a*—normal unequalized fourth-order Butterworth high-pass configuration with $f_3 = f_B = 40$ Hz; *b*—stepped-down equalized sixth-order pseudo-Butterworth configuration with $f_3 = f_B = 28$ Hz.

modification somewhat reduces the maximum acoustic output capabilities of the system in the 35–70-Hz range, but greatly increases the maximum output below 35 Hz (Fig. 4, also see Appendix I). For example, at 25 Hz the unequalized B_4 system can generate a maximum of only 0.01 acoustic watt, while the B_6 equalized system can radiate 0.16 watt, a jump of some 12 dB.

SUMMARY

A new set of assisted vented-box alignments allows the designer to utilize the many advantages of higher order configurations with drivers whose resonance frequencies do not coincide with desired system cutoff. The use of these higher order vented alignments offers real advantages in providing maximum useful low-frequency acoustic output while minimizing driver diaphragm excursion both in and out of the systems operating frequency range. In some cases an extension of low-end response an octave below driver free-air resonance can be obtained in a relatively small box.

APPENDIX I

MAXIMUM ACOUSTIC OUTPUT POWER

Unfortunately, loudspeaker systems are more often described by how much electrical power they can soak up without disintegrating, rather than by how much acoustic power they can pump out at an acceptable level of distortion. After all is said and done, it is the power out, in conjunction with the acoustic characteristics of the listening environment, that determines the sound pressure levels (SPL) attainable.

For the systems analyzed in this paper, curves are shown that indicate, at each frequency, the maximum acoustic power output and SPL generated in the reverberant field of a reference environment [85-m³ (3000-ft³) room with a 200-sabin room constant, a moderately large somewhat live living room] before 1) the driver burns itself up (driver thermal limit) or 2) distortion becomes too high (driver displacement limit), whichever occurs first. The low-frequency maximum power output of a driver is found to be highly dependent on the type of enclosure it is used in. Frequency response equalization (if used), of course, has no effect on maximum acoustic output.

Ideally, a system should be thermally limited over its full operating frequency range. Displacement limiting implies that the system's input electrical power must be decreased below the driver's thermally limited maximum input power $P_{E(\max)}$, or distortion will become too high. The computer model used in this paper assumes that the driver's cone displacement is linear up to $\pm x_{\max}$ (distortion acceptable) and nonlinear beyond (distortion unacceptable). The system's displacement limited maximum output power is the power the system can generate when the cone excursion is $\pm x_{\max}$.

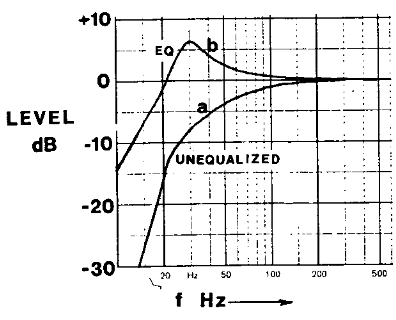

Fig. 3. Low-frequency response. *a*—unequalized 380-mm (15-in) vented-box system with box tuned to 28 Hz; *b*—second-order high-pass-filter equalizer which supplies 6 dB peak boost at 30 Hz.

APPENDIX II

A SIXTH-ORDER SYSTEM DESIGN USING A TYPICAL ACOUSTIC SUSPENSION DRIVER

The CTS 12W32C 30.5-mm (12-inch) driver represents a unit that would typically be used in a closed-box system of roughly 40 liters (1.4 ft³) net internal volume. The resultant system would provide a low-frequency cutoff (−3 dB) of roughly 60 Hz with about 0.5-dB ripple in the passband. When the same driver is used in a 113-liter (4 ft³) vented-box aligned to a sixth-order assisted configuration, the cutoff is extended down to 26 Hz (46 Hz without EQ). At 25 Hz the vented system can radiate more than six times (8 dB) the acoustic power of the closed-box system before the thermal input power ratings of the driver are exceeded.

Driver Parameters

The Thiele/Small parameters of the CTS 12W32C low-resonance high-compliance driver are listed as follows (parameters courtesy of J. R. Ashley):

$f_S = 22$ Hz
$Q_{ES} = 0.28$
$Q_{MS} = 2.2$
$Q_{TS} = 0.25$
$V_{AS} = 414$ liters (14.7 ft³)
$\eta_0 = 1.2\%$ (half-space
Effective diameter = 230 mm (9.4 in)
$x_{\max} = 6.4$ mm (0.25 in)
$V_D = 0.280$ liter (17.3 in³)
Advertised diameter = 305 mm (12 in)
$P_{E(\max)} = 40$ watts
$R_E = 5.8$ ohms

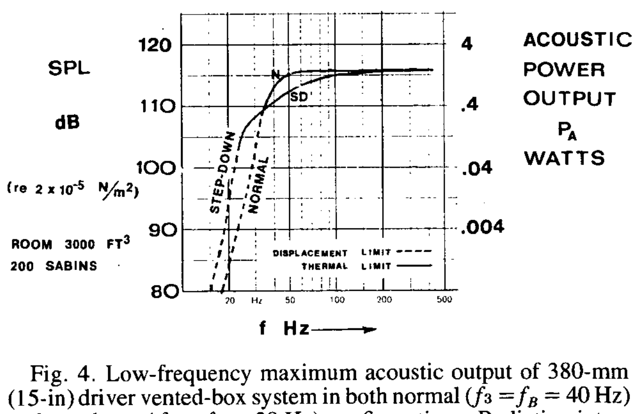

Fig. 4. Low-frequency maximum acoustic output of 380-mm (15-in) driver vented-box system in both normal ($f_3 = f_B = 40$ Hz) and stepdown ($f_3 = f_B = 28$ Hz) configurations. Radiation into a half-space is assumed with equivalent sound pressure levels generated in 85-m³ (3000-ft³) room (reverberant field) with a 200-sabin room constant. Maximum output is limited by driver thermal (solid line) or displacement (dashed line) capabilities.

where

f_S	resonance frequency of unenclosed driver
Q_{ES}	Q of driver at f_S considering electrical resistance R_E only
Q_{MS}	Q of driver at f_S considering driver nonelectrical resistances only
Q_{TS}	total Q of driver at f_S considering all driver resistances
V_{AS}	volume of air having same acoustic compliance as driver suspension ($= \rho_0 c^2 C_{AS}$)
η_0	reference efficiency (half-space)
x_{max}	peak linear displacement limit of driver diaphragm
V_D	peak displacement volume of driver diaphragm ($=S_D x_{max}$)
S_D	effective projected surface area of driver diaphragm
$P_{E(max)}$	thermally limited maximum input power
R_E	dc resistance of driver voice coil.

Three separate systems were designed for this driver and analyzed by computer model for frequency response and maximum acoustic power output (Figs. 5 and 6, also see Appendix I).

Closed-Box System

Small [9] covers the design of the closed-box speaker system very thoroughly. A 0.5-dB ripple second-order Chebyshev response C_2 was selected for this unit which requires a driver-to-box-volume ratio ($\alpha = V_{AS}/V_B$) of 10.5. Thus $V_B = V_{AS}/10.5 = 39.4$ liters (1.4 ft^3). The frequency response is shown in Fig. 5 and the maximum acoustic output curve is shown in Fig. 6. This system stays thermally limited for all frequencies and exhibits an f_3 of 63 Hz. To simplify the modeling, a minimal amount of enclosure stuffing was assumed.

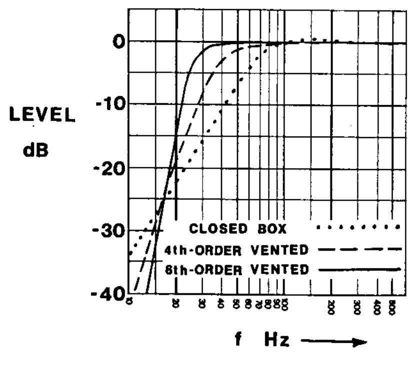

Fig. 5. Low-frequency responses of a typical high-compliance long-throw low-resonance low-Q_T "acoustic-suspension" type 305-mm (12-in) driver used in three different types of enclosure systems:
1) 39.4-liter (1.4-ft^3) second-order C_2 closed-box system with $f_3 = 63$ Hz
2) 113-liter (4-ft^3) fourth-order QB_3 vented-box system with $f_3 = 39$ Hz ($f_B = 33$ Hz)
3) 113-liter (4-ft^3) sixth-order QB_6 equalized vented-box system with $f_3 = 26$ Hz ($f_B = 26$ Hz).

Note the extension of low-end response that the sixth-order vented-box system provides.

Vented QB_3 System

The driver is found to roughly fit the quasi-Butterworth third-order alignment 3 of Thiele [1]. From Thiele's Table I comes $f_B/f_S \approx 1.5$ and $\alpha \approx 4.5$. Therefore $f_B = 1.5, f_S = 33$ Hz, and $V_B = V_{AS}/4.5 \approx 113$ liters (4 ft^3). The box has been overvolumed by about 20% to compensate for box losses.

The computer-predicted response and acoustic output curves are shown in Figs. 5 and 6. The computer simulates a lossy vented box by assuming a finite leakage loss Q of 7 ($Q_B = Q_L = 7, Q_P = Q_A = \infty$) [10, p. 366]. This system provides an f_3 of 39 Hz and is thermally limited above 27 Hz. The electrical input power to this system below 20 Hz must be limited to 10 watts so as not to exceed the driver's excursion capabilities.

Vented Sixth-Order System

Using Eqs. (7) and (8) or Table I yields $f_B = f_{aux} = 26$ Hz and $V_B = 113$ liters (4 ft^3), overvolumed again as before. The peak boost of 6 dB for the auxiliary circuit occurs at $1.07 f_B = 28$ Hz. Figs. 5 and 6 again show the response and maximum acoustic outputs for this system. The system f_3 is 26 Hz (with EQ) and stays thermally limited down to 21 Hz. The high-pass action of the equalizer circuit very nicely protects the system from below-band high-level subsonic signals, thus minimizing intermodulation and Doppler distortion.

APPENDIX III

A SIXTH-ORDER DESIGN USING A LOW-COMPLIANCE SHORT-THROW DRIVER

A hypothetical 203-mm (8-in) driver with high resonance frequency, high Q_T, small excursion capabilities, and low thermal limit input power rating was selected here for a comparative analysis using the three types of systems. Again the sixth-order assisted alignments are found to provide some very real advantages in extending low-end response and increasing the low-frequency maximum acoustic output of these kinds of "old dog" drivers.

For this hypothetical driver, the low-end f_3 shifts from 95

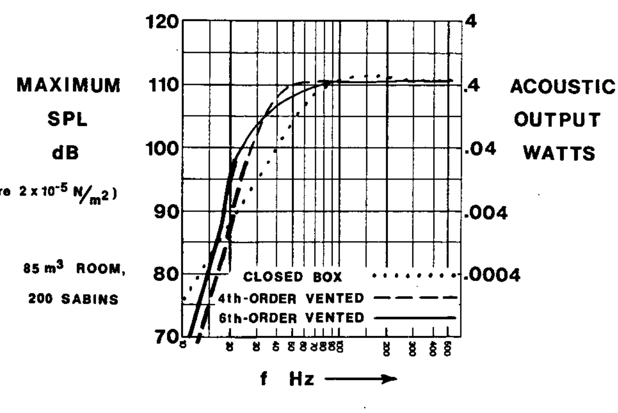

Fig. 6. Low-frequency maximum acoustic output power and sound pressure level curves for driver and systems of Fig. 5. The sixth-order vented configuration provides some 5–10 dB more maximum output in the important 20–45-Hz range than the closed-box system. Light lines indicate thermally limited operation and heavy lines displacement-limited operation.

Hz down to 38 Hz (75 Hz without EQ) when the closed-box is changed over to the sixth-order vented system. Using this rather anemic driver with a 15-watt amplifier, very usable maximum SPLs greater than 97 dB can be generated at 40 Hz and above in the 85-m^3 (3000-ft^3) reference environment.

Driver Parameters

The cooked-up hypothetical driver has the following Thiele/Small parameters:

$f_S = 90$ Hz
$Q_{ES} = 1.3$
$Q_{MS} = 1.5$
$Q_{TS} = 0.7$
$V_{AS} = 14.2$ liters (0.5 ft^3)
$\eta_0 = 0.76\%$ (half-space)
Effective diameter = 165 mm (6.5 in)
$x_{max} = 1.8$ mm (0.071 in)
$V_D = 0.038$ liter (2.36 in^3)
Advertised diameter = 203 mm (8 in)
$P_{E(max)} = 15$ watts.

As before, three systems were designed for this driver and computer analyzed for response and maximum output.

Closed-Box System

A relative large closed-box enclosure [$\alpha = 0.5$, V_B = 28.3 liters (1 ft^3)] was modeled in an attempt to salvage some of the low end of this somewhat anemic driver. The resultant C_2 response exhibits 0.5-dB passband ripple with an f_3 of about 95 Hz (Fig. 7). The maximum acoustic output is shown in Fig. 8. The system is slightly displacement limited by an average of 0.2 dB below 85 Hz.

Vented C_4 System

The Chebyshev unassisted fourth-order alignment 9 of Thiele was selected for the driver. A Q_T error of about 0.7/0.56 = 1.25 ($\approx$ + 2 dB) exists. Thiele's Table I provides $f_B/f_S \approx 0.72$ and $\alpha \approx 0.49$; therefore $f_B = 65$ and V_B = 37 liters (1.3 ft^3) (allowing 27% overvolume to compensate for box losses).

Figs. 7 and 8 show the response and output for this system. The response has a 2-dB passband ripple with an f_3 of 55 Hz. Observe that both f_3 and the thermal limit frequencies have shifted down by a factor of about 0.6 when the switch from closed to vented systems is made. Note, however, that even though the vented system has higher maximum output in the 45–150-Hz range, the closed-box system output is higher below 45 Hz. The fourth-order vented system initial rolloff rate below 55 Hz is seen to approach 36 dB per octave.

Vented Sixth-Order System

Application of Eqs. (7) and (8) yields $f_B = f_{aux} = 45$ Hz and V_B = 20.5 liters (0.72 ft^3). To offset box losses and flatten the response, f_B was lowered slightly to 43 Hz and box volume increased to 37 liters (1.3 ft^3). The auxiliary filter provides a 6-dB boost at 46 Hz. The frequency response and maximum acoustic output are shown again in Figs. 7 and 8 along with the C_2 and C_4 curves for comparison. Note the low-end and thermal limit extension down to less than 40 Hz. Observe that the system at 40 Hz can generate some 11 dB (12.5 times) more maximum output than the closed-box system without exceeding the ±2-mm displacement rating of the driver.

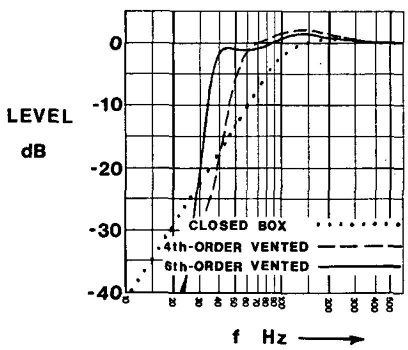

Fig. 7. Low-frequency responses of a low-compliance short-throw high-resonance high-Q_T 203-mm (8-in) driver used in three different types of enclosure systems:
1) 28.3-liter (1-ft^3) second-order C_2 closed-box system with f_3 = 95 Hz
2) 37-liter (1.3-ft^3) fourth-order C_4 vented-box system with f_3 = 55 Hz (f_B = 65 Hz)
3) 37-liter (1.3-ft^3) sixth-order C_6 equalized vented-box system with f_3 = 38 Hz (f_B = 43 Hz).

APPENDIX IV

DRIVER AND BOX PARAMETERS FOR THE 380-mm VENTED SYSTEM

The Thiele/Small parameters of the 380-mm (15-in) driver used in the vented system described in Figs. 2–4 are the following:

$f_S = 40$ Hz
$Q_{ES} = 0.42$
$Q_{MS} = 4.0$
$Q_{TS} = 0.38$
$V_{AS} = 227$ liters (8.0 ft^3)
$\eta_0 = 3.3\%$ (half-space)

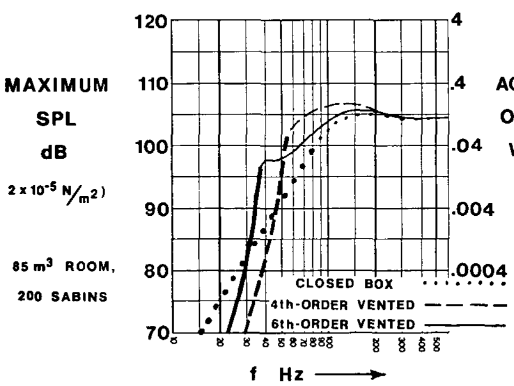

Fig. 8. Low-frequency maximum acoustic output power and sound pressure level curves for driver of Fig. 7. The sixth-order setup again provides a healthy increase in maximum output in the lowest octave of operation. Light lines indicate thermally limited operation and heavy lines displacement-limited operation.

Effective diameter = 330 mm (12 in)
x_{max} = 4.3 mm (0.17 in)
V_D = 0.37 liter (22.5 in^3)
Advertised diameter = 380 mm (15 in)
$P_{E(max)}$ = 50 watts
R_E = 6.5 ohms.

When this driver is used in a vented box of 212 liters (7.5 ft^3) tuned to 40 Hz, the response is approximately a fourth-order Butterworth high-pass with f_3 = 40 Hz. This is a Thiele alignment 5 with the box 30% overvolumed to offset box losses. The system can generate 1.6 acoustic watts mid-band into a half-space acoustic load.

ACKNOWLEDGMENT

I am indebted to my colleague at Electro-Voice, Ray Newman, for first discovering that the fourth-order vented response could be changed into the sixth-order response by lowering of the box tuning by $1/\sqrt{2}$ and the addition of second-order high-pass filter with a Q of 2. (When the first experimental enclosure was measured, we both marveled at how well the 6-dB peak-lift filter equalized the response. The research described in this paper came way after the first model was constructed and explains quite nicely why the equalizer filter did work so well).

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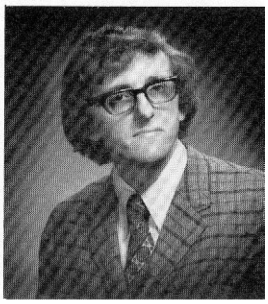

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