UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

Design of bass-reflex loudspeakers: the standard alignment

Castells Ramón, Francisco (fcastells@eln.upv.es)

Departamento de Ingeniería Electrónica
Universitat Politècnica de València

Contents

1 Summary of key ideas

This document provides the insights about the design process of bass-reflex systems (also known as vented enclosures). Bass-reflex systems are designed to take advantage of the radiation from the rear side of the cone, which is disregarded in closed-box loudspeaker (and transformed into heat within the absorbent material). This can be achieved by shifting the phase of the rear wave through an acoustic filter, composed by an acoustical compliance (provided by the enclosure) and an acoustical mass, which can be provided by a ported vent or tube. The enclosure and the port constitute an acoustical resonator, also known as Helmholtz resonator. At the resonance frequency f_{B} (Helmholtz frequency), the radiation of the system is mainly produced by the port. As f_{B} is usually tuned at low frequencies, vented enclosure systems offer extended bass response, which is an improved feature respect to closed boxes.

Oppositely to sealed enclosures, where the design is dominated by the box volume, in vented enclosures there are two degrees of freedom: V_{B} and f_{B}. This makes the design somehow more complex. Furthermore, a reasonably flat response is not guaranteed, which obligates to a trial and error procedure involving two variables (and hence, with infinite combinations). Nevertheless, despite these problems, due to the unquestionable advantages, vented enclosure designs are, by far, the choice for most loudspeaker systems. A way to avoid that tedious trial and error process is through the standard alignment, which provides, for a given transducer, the required V_{B} and f_{B} to obtain a relatively flat frequency response. The limitations and criticisms to the standard alignment is that the design is unique for each specific driver. Even though, this solution has been widely spread, and mastering the standard bass-reflex design is nowadays considered to be a must in loudspeaker industry.

2 Introduction

The scheme of a vented enclosure is illustrated in Figure 1. The total ratiation is the result of the joint radiation of the cone and the port. If the system is well designed, the cone and the port cooperate in a virtuous manner, such that the sound pressure response of the cone is extended at the low frequency side by the effect of the port radiation.

In bass-reflex systems, lining with damping material is used to prevent standing waves due to reflections of the rear wave, but special attention should be paid to avoid obstructing the passage of the acoustic wave through the port and hindering the resonance effect. Therefore, heavy filling is not recommended in this case. Three loss factors due to leakage, absorption within the damping material and losses in the port arise in vented enclosures, being the overall loss factor dominated by leakage. Generally speaking, the larger the size of the box, the higher the losses due to leakage.

The design of bass-reflex systems mainly involves driver selection and fixing the internal volume of the box V_{B} as well as the tuning frequency f_{B}. All this together will determine the frequency response of the loudspeaker system in terms of lower cutoff frequency and flatness.

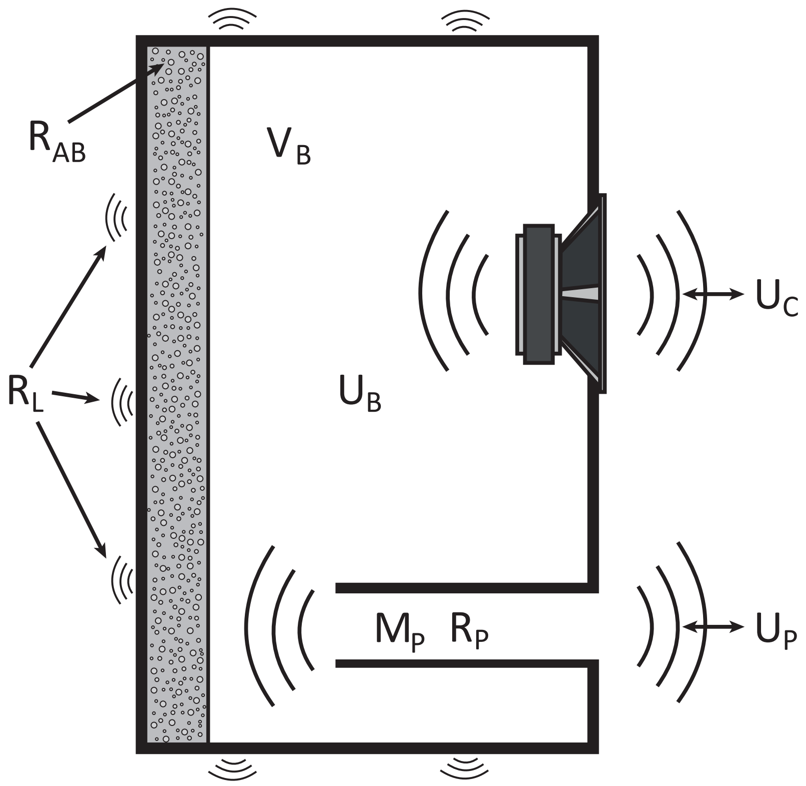

Figure 1: Scheme of a vented enclosure.

2.1 Previous requirements

To achieve the full learning potential of this material you should master the concepts regarding the dynamic speaker, including the equivalent circuit, electromechanical and linear parameters as well as the characteristic curves.

3 Objectives

After reading this document you will be able to:

- Identify the key parameters of the driver for a bass-reflex design.
- For a given driver, identify the normalized coefficients corresponding to the standard alignment and, accordingly, compute the box volume V_{B} and the Helmholtz frequency f_{B}.
- Determine the lower cutoff frequency and flatness of the frequency response.

4 Development

4.1 Frequency response of vented enclosures

The most appropriate way to evaluate the frequency response of vented enclosures is from the analysis of the equivalent mechanical circuit, which is shown in Figure 2. The elements introduced by the enclosure are the equivalent mechanical compliance C_{MB} due to box volume, the mechanical mass M_{MP} due to the vented port and the resistance R_{ML} corresponding to leakage losses.

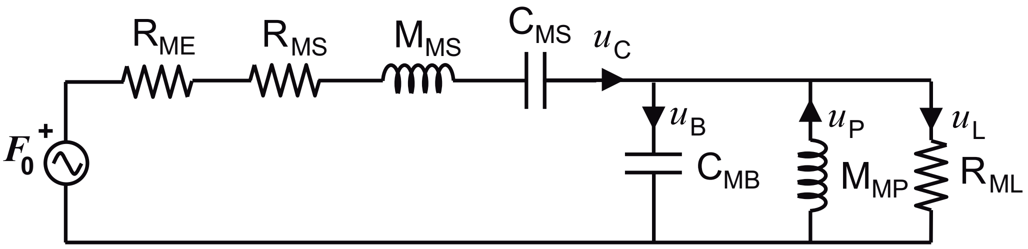

Figure 2: Mechanical equivalent circuit of a vented enclosure.

In order to understand the behavior of this circuit, let us focus on the interaction between the box compliance and the port as a parallel resonator. The Helmholtz frequency f_{B} is given by the following expression:

$$f_{\mathrm{B}} = \frac{1}{2\pi\sqrt{C_{\mathrm{MB}}M_{\mathrm{MP}}}} \tag{1}$$

At this frequency, the impedances of C_{MB} and M_{MP} cancel each other, which means that the parallel impedance becomes maximal and equals R_{ML}. As a consequence, the cone velocity u_{C} drops drastically, being only limited by enclosure leaks (in the case of an ideal case with null leaks, $R_{\mathrm{ML}} \longrightarrow \infty$ and u_{C} is null at f_{B}), which makes the port velocity u_{P} being the main contribution to the acoustic radiation. Figure 3 illustrates the frequency response of a bass-reflex system with $Q_{\mathrm{L}} \to \infty$, including cone, port and total radiation. Notice how the port radiation extends the bass response. However, as can be appreciated, the slope outside the bandpass decreases asymptotically at a rate of 24dB/oct, in contrast with sealed enclosures, with a slope of 12dB/oct.

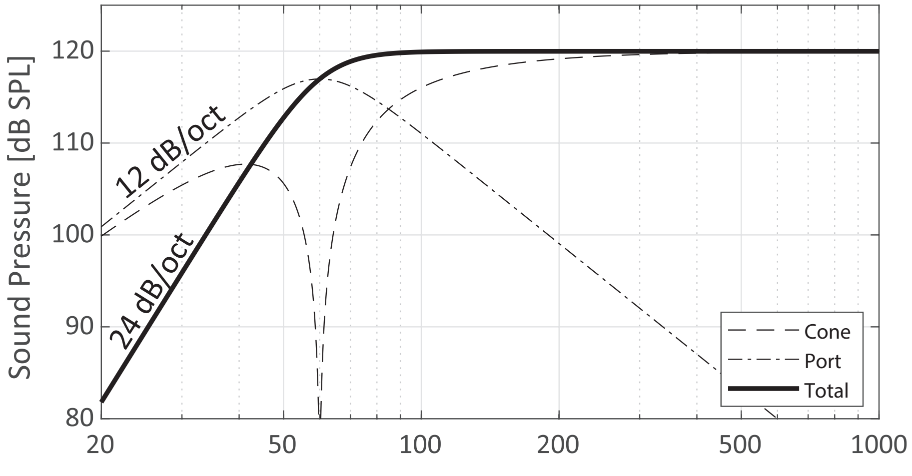

Figure 3: Example of SPL curves (cone, port and total radiation) for vented enclosures.

Given a specific driver, the design of vented enclosures essentially involves the choice of two parameters: V_{B} and f_{B}. Oppositely to closed boxes, where a single degree of freedom is given, the design of vented enclosures presents two degrees of freedom, which certainly complicates the task of design. Furthermore, enclosure leaks also play a role in the frequency response. As the volume increases, leakage losses are more prone to increase, so Q_{L} decreases accordingly. For unexperienced designers, the recommendation is to consider $Q_{\mathrm{L}} = 15$ for small boxes (up to 20 liters), $Q_{\mathrm{L}} = 7$ for medium-size boxes (between 20 ad 80 liters) and $Q_{\mathrm{L}} = 3$ large boxes (above 80 liters).

Reaching a correct combination of V_{B} and f_{B} that satisfies the enclosure requirements is not a simple task. Let us consider an example where a driver is aligned with different combinations

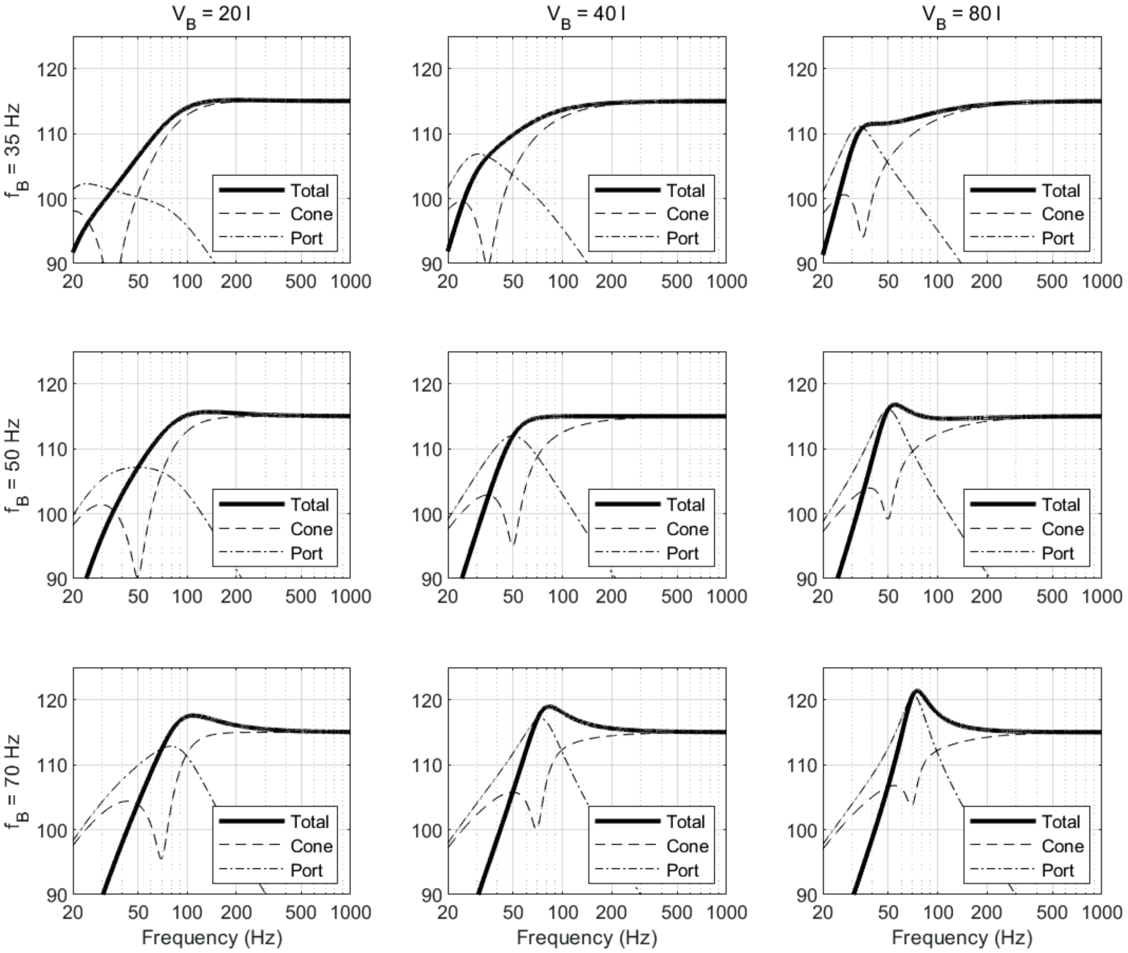

Figure 4: Effects of V_B and f_B tuning combinations on the frequency response.

of V_B and f_B, as shown in Figure 4 ($Q_\mathrm{L} = 7$ was considered in all cases). As can be observed, the SPL of the port becomes more peaky and with higher amplitude as f_B and/or V_B increase. Actually, the frequency response of the total radiation is not that easy to predict. In occasions, the frequency at which the port beams radiation is too low to be effective. Other times, the port radiation is so weak that scarcely extends the lower cutoff frequency in few Hz. On the contrary, the port radiation may exceed in several dB the radiation of the cone, therefore causing a pronounced boost at low frequencies. In any of these cases, the contribution of the port would not be much beneficial. Consequently, finding a satisfactory solution involves a cumbersome trial and error process that can only come to fruition with a high dose of patience and perseverance.

4.2 The standard alignment

Considering the normalized coefficients α and $f_\mathrm{B}/f_\mathrm{s}$, where

$$\alpha = \frac{V_\mathrm{AS}}{V_\mathrm{B}}, \tag{2}$$

the term alignment refers to a particular combination of α and $f_\mathrm{B}/f_\mathrm{s}$ that searches for some properties of the frequency response. The most extended alignment families are the unassisted 4th-order Butterworth (B4), the 3rd-order Quasi-Butterworth (QB3) and the 4th-order Chebyshev (C4) alignments, whose frequency response are shown in Figure 5.

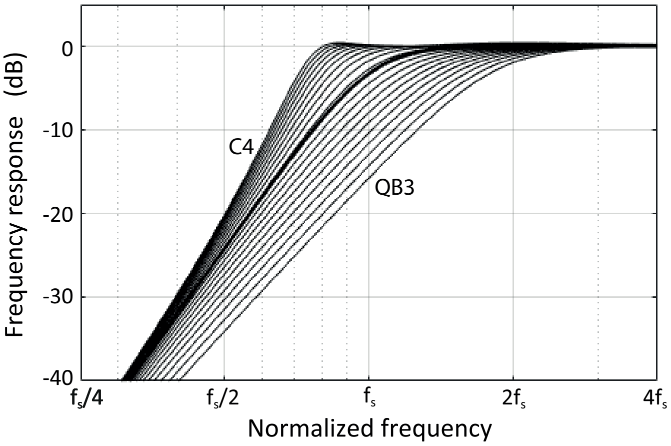

Figure 5: Frequency response shapes for the C4, B4 (thick line) and QB3 alignments.

For a given transducer, the standard alignment is essentially determined by Q_{TS} and is moderately sensitive to Q_{L}, and can be determined by reading α and $f_{\mathrm{B}}/f_{\mathrm{s}}$ from a table. Table 2, Table 3 and Table 4 are the tables of the standard alignment for $Q_{\mathrm{L}} = 15$, $Q_{\mathrm{L}} = 7$ and $Q_{\mathrm{L}} = 3$, respectively, which are available at the end of this document. Consider for instance Table 3 ($Q_{\mathrm{L}} = 7$). In this case, the B4 alignment can only be achieved for a unique value of Q_{TS} ($Q_{\mathrm{TS}} = 0.4048$). For this reason, the B4 alignment is said to be a discrete alignment. For drivers with lower Q_{TS}, the standard alignment will be QB3, whereas for drivers with higher Q_{TS} the alignment will be C4 (check the values of Q_{TS} corresponding to the discrete B4 alignment for different values of Q_{L}).

The standard alignment of a driver can be determined as follows:

1. From the driver's datasheet, read the value of Q_{TS}.
2. Take the values of α from Table 2, Table 3 and Table 4.
3. For each table, compute the box volume as:

$$V_{\mathrm{B}} = \frac{V_{\mathrm{AS}}}{\alpha} \tag{3}$$

   and choose the appropriate table that provides a consistent box volume according to its Q_{L}.

4. Take the value of $f_{\mathrm{B}}/f_{\mathrm{s}}$ and compute the Helmholtz frequency as:

$$f_{\mathrm{B}} = \left(\frac{f_{\mathrm{B}}}{f_{\mathrm{s}}}\right) f_{\mathrm{s}} \tag{4}$$

The lower cutoff frequency of the system frequency response can be also estimated from the parameter f_6/f_{s} (or, alternatively, from f_3/f_{s} or f_{10}/f_{s}), which can be also read from the tables:

$$f_6 = \left(\frac{f_6}{f_{\mathrm{s}}}\right) f_{\mathrm{s}} \tag{5}$$

	$Q_{\mathrm{L}} = 15$	$Q_{\mathrm{L}} = 15$	$Q_{\mathrm{L}} = 15$
α	0.8787	0.8266	0.7225
V_{B}	262l	279l	320l

Table 1: α and V_{B} for the Beyma 18LEX1600ND according to different Q_{L} values.

Example

In this example we will determine the standard alignment for the driver Beyma 18LEX1600ND, with $Q_{\mathrm{TS}} = 0.43$, $f_{\mathrm{s}} = 33$Hz and $V_{\mathrm{AS}} = 231$l. From Table 2, Table 3 and Table 4, we read the values of α for this Q_{TS}, which are given in Table 1. From them, and V_{AS}, the corresponding volumes V_{B} are computed (see also Table 1). From all these possibilities, which one do you think is to be used? As V_{B} is clearly over 80l in all cases, $Q_{\mathrm{L}} = 3$ becomes the unique consistent option.

From Table 4 it comes that, for $Q_{\mathrm{TS}} = 0.43$, a QB3 frequency response will be obtained, just at the borderline with B4. To achieve such a frequency response, $f_{\mathrm{B}}/f_{\mathrm{s}} = 1.0195$, so that the Helmholtz frequency f_{B} should be tuned to 34Hz. With this standard alignment, we obtain a frequency response with no ripple and a lower cutoff frequency $f_6 = 30$Hz, which provides a really deep bass response (this is indeed a great performance) that could never be achieved for this driver with a closed-box design.

5 Closing remarks

After reading this document you are now able to determine the standard alignment for vented enclosures. This solution is unique for a given driver, which mainly depends on Q_{TS} and is mildly influenced by Q_{L}. The pros of the standard alignment is that it guarantees a relatively flat frequency response.

On the other hand, the main criticisms to the standard alignment is that it does not exploit all the possibilities for designing vented enclosures. If, after a design based on the standard alignment, you are not satisfied with either V_{B} or f_6 (in the example above, the 320l box could be too large for your design), you can still search for other solutions with different combinations of V_{B} and f_{B}. However, this would unavoidably require a trial and error procedure that can only be lightened by the art of experience.

References

[1] Leo L. Beranek and Tim J. Mellow. Acoustics: Sound Fields and Transducers. Elsevier Academic Press, 2012.

[2] Vance Dickason. Loudspeaker Design Cookbook 7th Edition. Segment LLC, 2005.

[3] John L. Murphy. Introduction to Loudspeaker Design. True Audio, 2014.

Q = 15

	Q_{TS}	α	$f_{\text{B}}/f_{\text{s}}$	f_3/f_{s}	f_6/f_{s}	f_{10}/f_{s}	R (dB)
	0.20	8.0331	1.8640	2.4512	2.0425	1.7024	0
	0.21	7.1822	1.7784	2.3225	1.9356	1.6137	0
	0.22	6.4446	1.7007	2.2045	1.8377	1.5326	0
	0.23	5.8010	1.6299	2.0960	1.7477	1.4582	0
	0.24	5.2361	1.5652	1.9956	1.6646	1.3895	0
	0.25	4.7375	1.5058	1.9023	1.5875	1.3259	0
	0.26	4.2952	1.4512	1.8153	1.5157	1.2668	0
	0.27	3.9011	1.4007	1.7338	1.4486	1.2118	0
	0.28	3.5484	1.3540	1.6471	1.3856	1.1604	0
	0.29	3.2314	1.3106	1.5846	1.3263	1.1123	0
QB3	0.30	2.9455	1.2703	1.5159	1.2704	1.0671	0
	0.31	2.6867	1.2327	1.4504	1.2175	1.0246	0
	0.32	2.4517	1.1976	1.3880	1.1673	0.9847	0
	0.33	2.2376	1.1648	1.3281	1.1197	0.9471	0
	0.34	2.0420	1.1341	1.2705	1.0744	0.9118	0
	0.35	1.8629	1.1052	1.2160	1.0313	0.8786	0
	0.36	1.6983	1.0781	1.1615	0.9904	0.8475	0
	0.37	1.5468	1.0526	1.1099	0.9517	0.8185	0
	0.38	1.4070	1.0286	1.0602	0.9150	0.7914	0
	0.39	1.2777	1.0059	1.0125	0.8806	0.7663	0
B4	0.3927	1.2444	1	1	0.8717	0.7598	0
	0.40	1.1591	0.9840	0.9675	0.8498	0.7437	0
	0.41	1.0535	0.9615	0.9262	0.8198	0.7215	0
	0.42	0.9604	0.9390	0.8884	0.7902	0.6996	0
	0.43	0.8787	0.9167	0.8539	0.7642	0.6799	0
	0.44	0.8074	0.8951	0.8226	0.7403	0.6616	0.01
	0.45	0.7453	0.8744	0.7942	0.7183	0.6445	0.02
	0.46	0.6911	0.8547	0.7684	0.6982	0.6288	0.03
	0.47	0.6439	0.8361	0.7451	0.6798	0.6143	0.05
	0.48	0.6027	0.8187	0.7239	0.6630	0.6010	0.07
	0.49	0.5666	0.8025	0.7047	0.6477	0.5887	0.09
	0.50	0.5348	0.7873	0.6873	0.6336	0.5775	0.12
	0.51	0.5068	0.7732	0.6714	0.6208	0.5671	0.16
C4	0.52	0.4820	0.7601	0.6569	0.6090	0.5576	0.20
	0.53	0.4599	0.7479	0.6437	0.5982	0.5488	0.24
	0.54	0.4402	0.7366	0.6315	0.5882	0.5407	0.29
	0.55	0.4225	0.7260	0.6204	0.5790	0.5331	0.34
	0.56	0.4065	0.7162	0.6101	0.5706	0.5262	0.39
	0.57	0.3921	0.7070	0.6006	0.5627	0.5197	0.45
	0.58	0.3789	0.6984	0.5919	0.5554	0.5137	0.51
	0.59	0.3670	0.6903	0.5838	0.5487	0.5081	0.57
	0.60	0.3560	0.6828	0.5762	0.5423	0.5028	0.63

Table 2: Standard alignment for $Q_{\text{L}} = 15$.

Q = 7

	Q_{TS}	α	$f_{\mathrm{B}}/f_{\mathrm{s}}$	f_3/f_{s}	f_6/f_{s}	f_{10}/f_{s}	R (dB)
	0.20	7.7775	1.9393	2.5289	2.1071	1.7561	0
	0.21	6.9524	1.8494	2.3968	1.9973	1.6650	0
	0.22	6.2372	1.7678	2.2759	1.8970	1.5818	0
	0.23	5.6132	1.6935	2.1647	1.8048	1.5054	0
	0.24	5.0655	1.6254	2.0620	1.7197	1.4351	0
	0.25	4.5822	1.5629	1.9667	1.6408	1.3700	0
	0.26	4.1535	1.5054	1.8778	1.5674	1.3095	0
	0.27	3.7714	1.4522	1.7946	1.4988	1.2532	0
	0.28	3.4295	1.4029	1.7165	1.4346	1.2006	0
	0.29	3.1223	1.3571	1.6429	1.3742	1.1513	0
QB3	0.30	2.8421	1.3145	1.5732	1.3173	1.1051	0
	0.31	2.5944	1.2748	1.5070	1.2635	1.0617	0
	0.32	2.3667	1.2376	1.4439	1.2125	1.0209	0
	0.33	2.1594	1.2028	1.3836	1.1641	0.9824	0
	0.34	1.9699	1.1702	1.3258	1.1182	0.9462	0
	0.35	1.7964	1.1395	1.2702	1.0745	0.9121	0
	0.36	1.6371	1.1106	1.2167	1.0329	0.8801	0
	0.37	1.4905	1.0834	1.1651	0.9934	0.8500	0
	0.38	1.3552	1.0578	1.1153	0.9559	0.8218	0
	0.39	1.2300	1.0335	1.0674	0.9204	0.7955	0
	0.40	1.1141	1.0106	1.0214	0.8870	0.7710	0
B4	0.4048	1.0613	1	1	0.8717	0.7598	0
	0.41	1.0070	0.9886	0.9777	0.8568	0.7488	0
	0.42	0.9113	0.9662	0.9373	0.8281	0.7275	0
	0.43	0.8266	0.9436	0.9001	0.7993	0.7062	0
	0.44	0.7521	0.9212	0.8660	0.7731	0.6864	0
	0.45	0.6868	0.8992	0.8348	0.7493	0.6681	0.01
	0.46	0.6297	0.8780	0.8064	0.7273	0.6511	0.01
	0.47	0.5798	0.8578	0.7804	0.7070	0.6353	0.02
	0.48	0.5361	0.8385	0.7567	0.6884	0.6206	0.03
	0.49	0.4978	0.8203	0.7351	0.6713	0.6070	0.05
	0.50	0.4642	0.8031	0.7155	0.6556	0.5944	0.07
	0.51	0.4345	0.7870	0.6975	0.6411	0.5828	0.09
C4	0.52	0.4083	0.7719	0.6810	0.6278	0.5721	0.12
	0.53	0.3849	0.7578	0.6659	0.6155	0.5621	0.15
	0.54	0.3640	0.7445	0.6526	0.6041	0.5529	0.19
	0.55	0.3453	0.7321	0.6393	0.5936	0.5443	0.23
	0.56	0.3284	0.7205	0.6275	0.5839	0.5363	0.27
	0.57	0.3131	0.7096	0.6166	0.5749	0.5289	0.31
	0.58	0.2992	0.6993	0.6065	0.5665	0.5219	0.36
	0.59	0.2865	0.6896	0.5971	0.5587	0.5154	0.41
	0.60	0.2749	0.6805	0.5883	0.5514	0.5094	0.46

Table 3: Standard alignment for $Q_{\mathrm{L}} = 7$.

Q = 3

	Q_{TS}	α	$f_{\mathrm{B}}/f_{\mathrm{s}}$	f_3/f_{s}	f_6/f_{s}	f_{10}/f_{s}	R (dB)
QB3	0.20	7.0552	2.1694	2.7548	2.2950	1.9123	0
	0.21	6.3041	2.0666	2.6125	2.1767	1.8141	0
	0.22	5.6531	1.9733	2.4824	2.0687	1.7245	0
	0.23	5.0851	1.8881	2.3630	1.9695	1.6422	0
	0.24	4.5866	1.8100	2.2528	1.8781	1.5665	0
	0.25	4.1467	1.7381	2.1508	1.7935	1.4965	0
	0.26	3.7566	1.6719	2.0559	1.7150	1.4316	0
	0.27	3.4090	1.6105	1.9674	1.6417	1.3712	0
	0.28	3.0980	1.5536	1.8845	1.5733	1.3149	0
	0.29	2.8186	1.5006	1.8065	1.5091	1.2622	0
	0.30	2.5666	1.4512	1.7331	1.4487	1.2128	0
	0.31	2.3386	1.4050	1.6636	1.3918	1.1663	0
	0.32	2.1317	1.3617	1.5978	1.3380	1.1226	0
	0.33	1.9432	1.3210	1.5351	1.2870	1.0815	0
	0.34	1.7712	1.2828	1.4754	1.2387	1.0426	0
	0.35	1.6136	1.2467	1.4183	1.1927	1.0060	0
	0.36	1.4690	1.2127	1.3636	1.1490	0.9713	0
	0.37	1.3360	1.1806	1.3110	1.1074	0.9386	0
	0.38	1.2133	1.1501	1.2605	1.0677	0.9077	0
	0.39	1.0999	1.1213	1.2118	1.0299	0.8786	0
	0.40	0.9949	1.0939	1.1649	0.9940	0.8511	0
	0.41	0.8974	1.0679	1.1198	0.9598	0.8253	0
	0.42	0.8069	1.0431	1.0763	0.9274	0.8010	0
	0.43	0.7225	1.0195	1.0346	0.8967	0.7783	0
B4	0.4386	0.6543	1	1	0.8717	0.7598	0
C4	0.44	0.6439	0.9979	0.9947	0.8682	0.7572	0
	0.45	0.5726	0.9744	0.9572	0.8423	0.7378	0
	0.46	0.5093	0.9515	0.9222	0.8164	0.7184	0
	0.47	0.4567	0.9286	0.8898	0.7905	0.6989	0
	0.48	0.4040	0.9059	0.8597	0.7672	0.6811	0
	0.49	0.3605	0.8837	0.8318	0.7457	0.6644	0
	0.50	0.3223	0.8621	0.8060	0.7256	0.6486	0.01
	0.51	0.2885	0.8412	0.7822	0.7068	0.6338	0.02
	0.52	0.2586	0.8212	0.7601	0.6893	0.6199	0.02
	0.53	0.2321	0.8021	0.7397	0.6730	0.6068	0.03
	0.54	0.2084	0.7838	0.7208	0.6578	0.5945	0.05
	0.55	0.1872	0.7664	0.7033	0.6436	0.5830	0.06
	0.56	0.1681	0.7499	0.6871	0.6303	0.5722	0.08
	0.57	0.1508	0.7341	0.6720	0.6180	0.5620	0.10
	0.58	0.1350	0.7192	0.6579	0.6064	0.5525	0.12
	0.59	0.1205	0.7049	0.6447	0.5955	0.5435	0.14
	0.60	0.1072	0.6913	0.6324	0.5852	0.5350	0.17

Table 4: Standard alignment for $Q_{\mathrm{L}} = 3$.