

## An Enclosure Design for TEBM35C10-4 BMR® Loudspeaker Driver

### Introduction

BMR is a patented loudspeaker technology that delivers true full range audio and wide directivity from a single drive unit. This is achieved by deterministic balancing of the modes to recover the ideal acoustic radiation characteristics of a flat, free panel. The TEBM35C10-4 is the latest addition to the BMR range, a small compact design whose high frequency output extends smoothly up to and beyond 20kHz. This driver is suitable for portable consumer and automotive applications. In this application note an enclosure is designed for the TEBM35C10-4 and a passive radiator (PR) is considered. Two box volumes are compared. Tuning of the PR to achieve smooth low-frequency response will be described. Extensive measurement was carried out on the prototypes, including measuring enclosure wall vibration. Lastly, the active equalization used to compensate for baffle step and tonal balancing will be discussed.

### Brief description of the driver

Key Thiele-Small (TS) parameters of the TEBM35C10-4 BMR driver are listed in Table 1. These are small-signal parameters where the diaphragm movement is minimal to maintain linear operation. Nonlinear effects on parameters such as  $Bl$  and  $Cms$  are not included. Users can import these small signal parameters and define a specific enclosure type in simulation design tools (e.g. AkAbak, LEAP-5, UniBox, WinSpeakerz) to predict performance, and perform iterative fine tuning.

The TEBM35C10-4 BMR driver has very wide directivity (up to  $180^\circ$ , see the TEBM35C10-4 datasheet for more information). In other words, its power response is smooth and extended, with minimal roll off with increasing frequency. These are crucial characteristics to obtain a natural listening experience in a room.

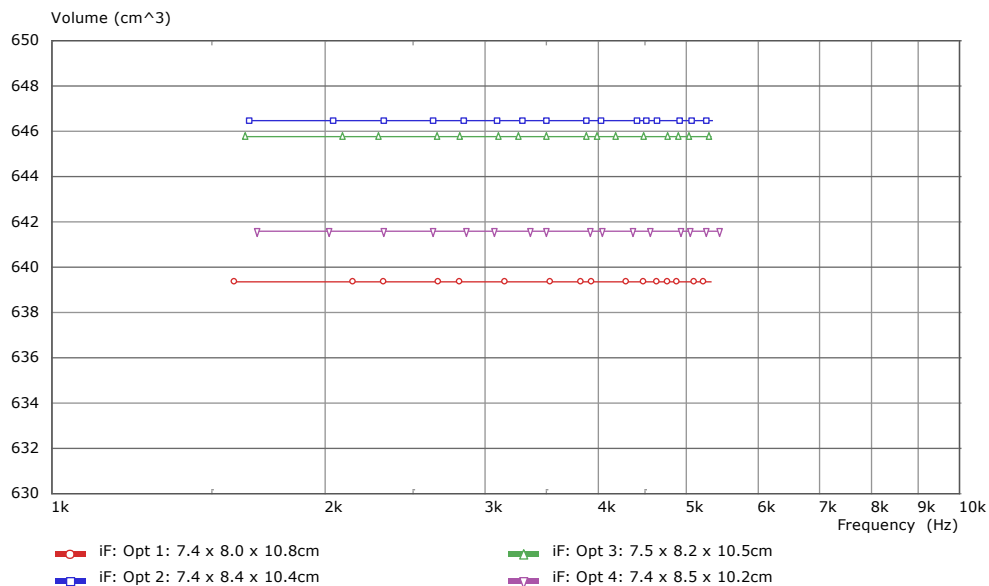
Fs	145 Hz
BL	1.94 Tm
Cms	1.04 mm/N
Mms	0.97 g
Re	4.2 $\Omega$
Qts	0.86
Xmax-mech	8 mm <sub>peak-to-peak</sub>

**Table 1. Key TS parameters of TEBM35C10-4 BMR driver.**

### Enclosure design and Passive Radiator (PR) tuning

A compact-sized enclosure is desired to demonstrate portability for a consumer application. In order to extend bass performance from this enclosure, a PR is considered. In contrast to a vented enclosure, using a PR allows very compact enclosures to be feasible. A vented enclosure may end up with a port length too long to fit inside the enclosure.

The enclosure shape was chosen to be a rectangular cuboid instead of a cube. A cube will encourage coincident (degenerate) internal standing waves due to equal distance of any two perpendicular walls. Rectangular boxes will spread standing waves frequencies, resulting in a more natural sound. A few candidate rectangular boxes of similar volume but with differing dimensions were considered. The candidates were selected based on practical considerations for mounting the driver and PR and aesthetic balance. An Eigenfrequency study of the internal pressure modes was then conducted using COMSOL Multiphysics. The key results from this study were a set of modes for each candidate enclosure. The selected enclosure dimensions were chosen based on the enclosure that gave the most evenly spaced distribution of these internal pressure modes, option 2 (blue) in Fig. 1, thus minimizing mode clusters that could result in noticeable colouration of the sound.



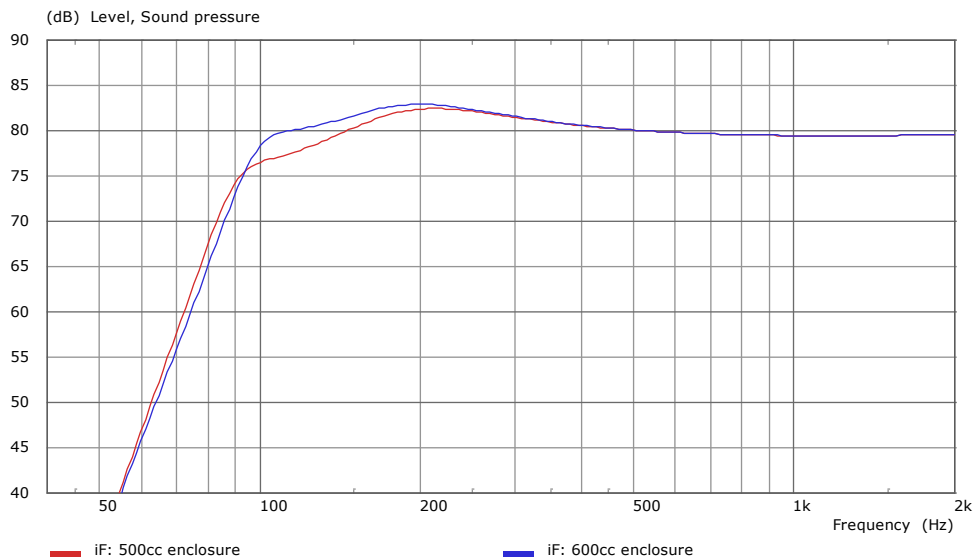
**Figure 1. FEA Eigenfrequency analysis of enclosure modes. Legends show inner dimensions in cm.**

Simulation of a 500 cc box and a 600 cc box was conducted to review difference in performance. A volume greater than 600cc was deemed too large for a portable demo. For each box volume, the PR was optimized. The compliance of the PR can be obtained from the stiffness of roll-surround. We used NBR shore 50A rubber for the surround. Typically value of the stiffness is 222N/m. Hence, the equivalent compliance is 4.5 mm/N. This is “theoretical” stiffness of surround used in simulation for optimizing PR’s. The piston diameter and moving mass of passive radiator were both optimized for each enclosure volume considered. The optimization process aimed to achieve maximum response flatness whilst

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ensuring safe peak excursion amplitude for the driver and passive radiator. The effective piston diameter of the PR for 500 cc and 600 cc box resulted in being 52 mm and 60 mm, respectively.

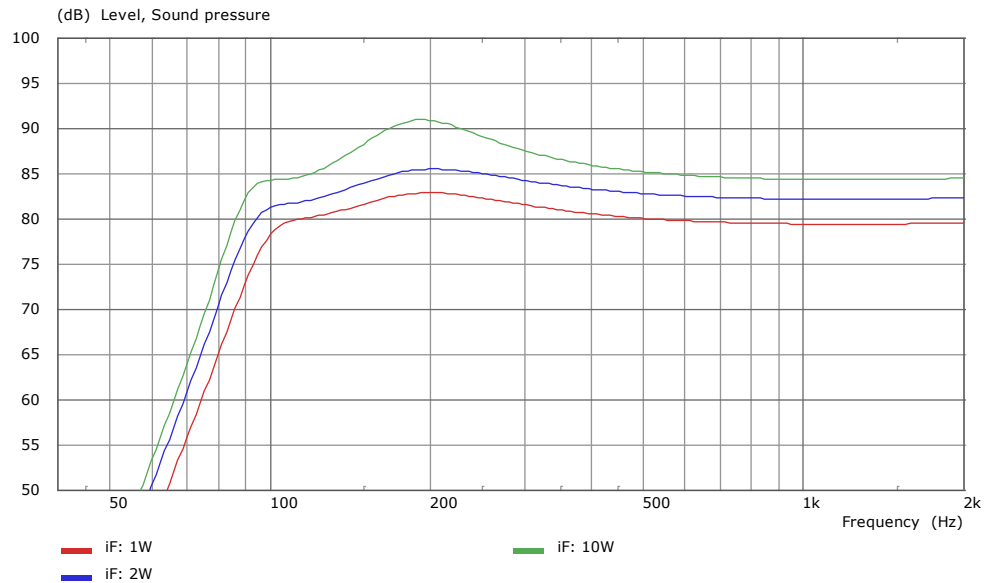
Simulated (infinite baffle) on axis SPL of the speaker in an enclosure volume equal to 500 cc and 600 cc box for 1 W input power, at 1m is illustrated in Fig. 2. The corresponding moving mass of PR was 3.5 g (500 cc) and 4.2 g (600 cc). These were optimized values for each box volume. We can see that 600 cc box provides a significant 2 dB additional SPL at 110 Hz. Hence, 600 cc acoustic volume was chosen. Outer dimensions are 11.0 x 9.2 x 8.0 cm, see Appendix 1 for more details. The dimensions are associated with Opt 2 inner dimensions shown in Fig. 1.



**Figure 2. Simulated (infinite baffle) on-axis SPL with PR.**

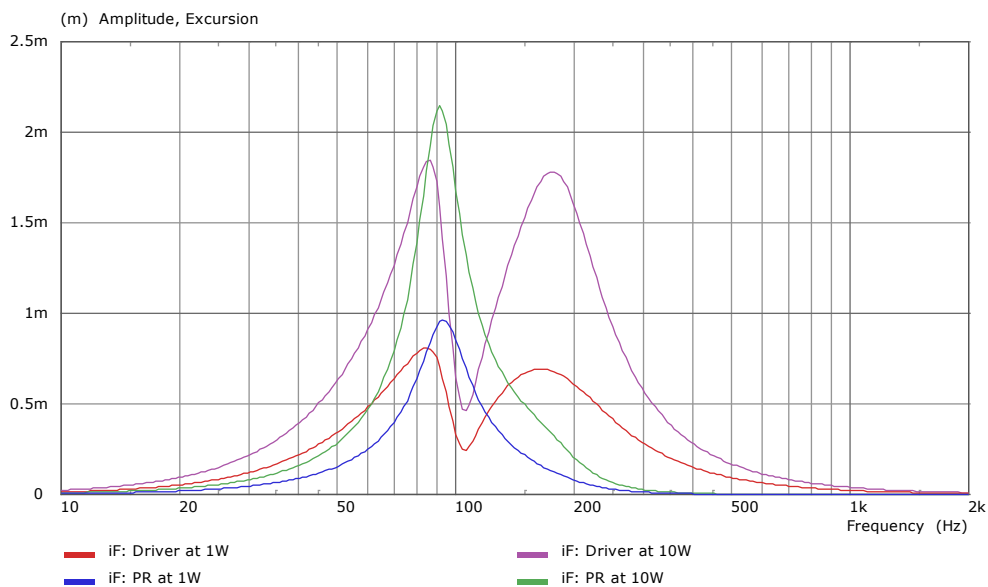
Impedance of a TEBM35C10-4 at different signal levels (e.g. 1V, 2V, 5V) was measured. The software (LEAP-5) used the measured data to generate a non-linear model. Further explanation is given in next section. SPL based on this non-linear model for 1 W, 2 W and 10 W are shown in Fig 3. We can see there is a bump at about 200 Hz emerging for higher input power. Simulation predicated that the driver was driven into nonlinear region where force factor (Bl) and suspension stiffness were no longer constants. Most drivers of similar size exhibit similar Qts change. The sonic effect can be managed by active equalization discussed in the following section.

It is important to note that the predicted non-linear behavior of the system as shown in figure 3 is very much a worst case scenario, and would not be observed with such severity when driven by real-world signals (e.g. music and speech material). Reference should be made to figure 9 where the system frequency response was measured over a similar range of input powers with a log chip type signal. Clearly the observed compression and Qts change is considerably more benign with this input signal, and a similar behavior is expected with typical music and speech.



**Figure 3. Simulated (infinite baffle) on-axis SPL of 600 cc box for 1 W, 2 W and 10 W input power.**

Driver and passive radiator peak excursion for 1 W and 10 W input power are illustrated in Fig. 4. A second-order 80 Hz high-pass-filter (HPF) was employed to protect the system. Crossover frequency of the HPF was chosen empirically to balance low-frequency extension and driver excursion. As can be seen, driver excursion for 10 W is well under the mechanical limit of 4 mm<sub>peak</sub>. The HPF is a stage of the active equalizer.



**Figure 4. Driver and PR peak excursion of 600 cc box for 1 W and 10 W input power. Second-order 80 Hz high-pass filter employed.**



**Figure 5. Outlook of 600 cc prototype. Outer/inner dimensions (WxHxD): 8.0 x 11.0 x 9.2 cm / 7.4 x 10.4 x 8.4 cm.**

### Measurement and Equalization

In order to minimize error between simulation and measurement, a PR sample was measured to get the actual moving mass and compliance. Deflection of the PR for added masses was measured by a laser displacement sensor (Panasonic HL-G108-A-CS). Results are given in table 2 below. Outer-half roll-surround of the PR is essentially not moving. Hence, the actual moving mass is 3.98 g.

Disc (g)	Inner-half surround (g)	Outer-half surround (g)	Moving mass (g)
3.57	0.41	0.78	3.57 + 0.41 = 3.98
Compliance Measurement			
Added mass (g)	Deflection (mm)		Compliance (mm/N)
5	0.16		3.27
10	0.32		3.27
20	0.68		3.47
40	1.41		3.60
50	1.70		3.47
Mean value			3.41

**Table 2. Measured moving mass and compliance of PR.**

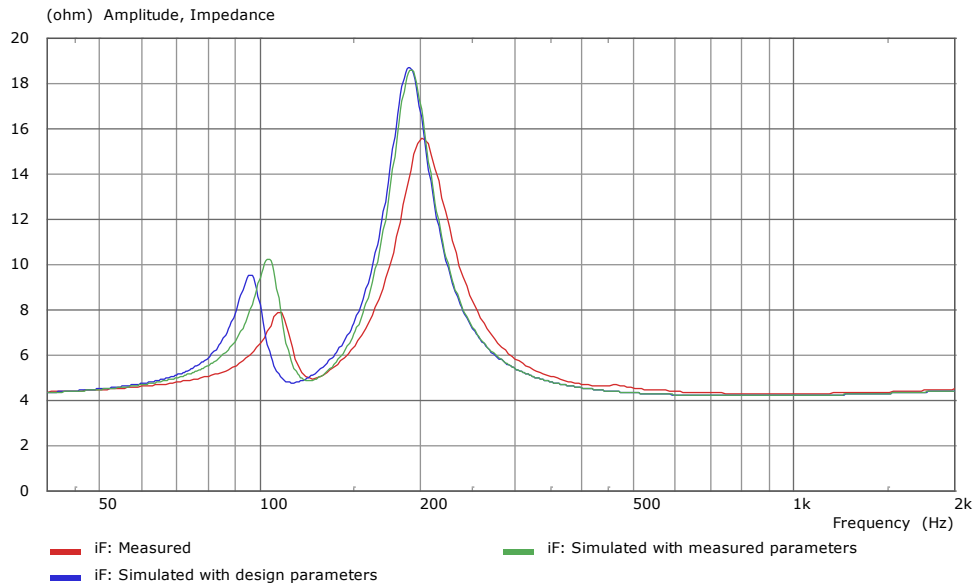
TS parameters of a TEBM35C10-4 driver were measured as well. Conventional TS parameters were derived from impedance measurements at a single signal level. The parameters such as  $B_l$ ,  $C_{ms}$  are assumed constant throughout the operating range. In practice, they are strongly dependent on signal level or excursion. LEAP-5 developed an advanced driver model which can predict the driver's nonlinearity under large-signal condition. The model requires a set of driver's impedance and terminal voltage measured at different signal levels. The model uses more parameters, as shown in Fig. 6 to model a driver.



Name	Model	Shape	Freq	KA	Fp	KA	Mass	g	Gms					
BMR25 FP2 #22 CLJD Pocket VI-data	LTD	Round	3.000		0.000		1.1500		4.4051					
	Drawn	Profile	Grid	Gls			Cms	mm/N	Ges					
	Freeze	Flat	1.000		2.000		965.3085m		1.3470					
Zmax	Xgap	M	Km	H	Kc	N-GM	Kcc	M/H	Vat	Lr	Qts			
4.000	2.500m		745.69100m	5.44430		24.10020	804.50220u		168.3408m		1.0316			
Revc	Xcol	M	Fm	Hr	Fm	Hr	Xcs	M	Kcc	M	Rms	N-SM	Levc	mm
4.100	3.800m		5.16230K	12.69700K			4.47020m		1.35460m		347.8643m		101.530m	
Sd	Xcas	M	Dms	Dsm	Dcs	Dcc					Fr	Hr	SPLo	dB
11.050	690.000u		1.24090	0.89047			0.29006		0.25762		151.1647		78.173	
Mmd	Kg	Xcg	M	Em	Exm	Erc	Ecc				BL	T-M	No	%
1.130m		622.117u		0.93567	0.43539		0.63707		0.00486		1.8240		0.0413	
Pmax	Wrat	Ebg	Vm	Vsm	Gm	Gcc					Vc	V	Ta	°C
500.000		14.99410		0.05701	0.02679		0.52479		1.14070		2.0000		25.00	
Rvc	C/A	BLo	T-M	Tm	Δ°C	Tsm	Δ°C				Trs	Δ°C	Tcs	Δ°C
500.000m		2.0619		0.000	0.000		0.000		0.000		0.000		0.000	

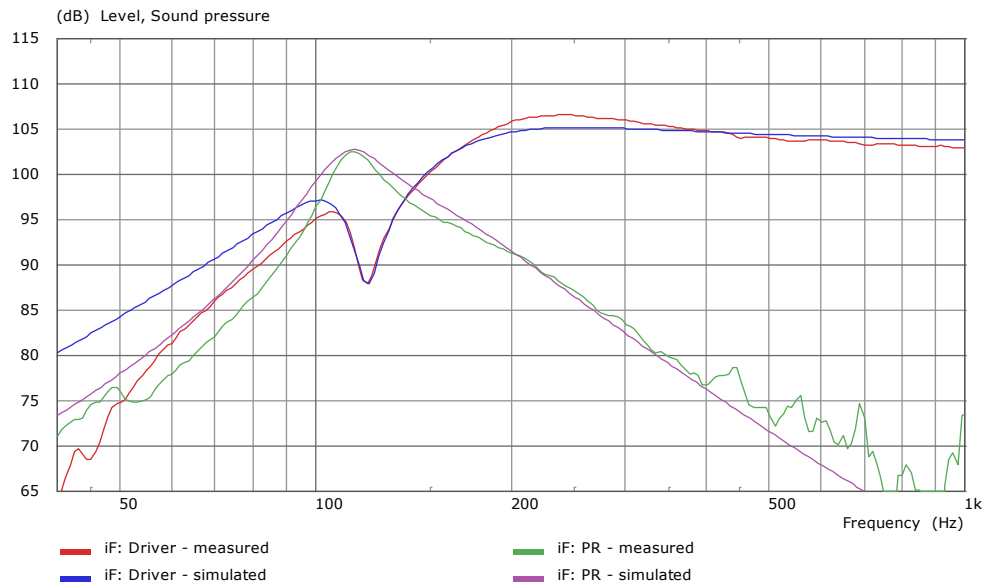
**Figure 6. LTD model of a TEBM35C10-4.**

Fig. 7 shows simulated impedance and measured impedance for the system. It can be seen simulation is closer to measurement when actual measured PR parameters were used.



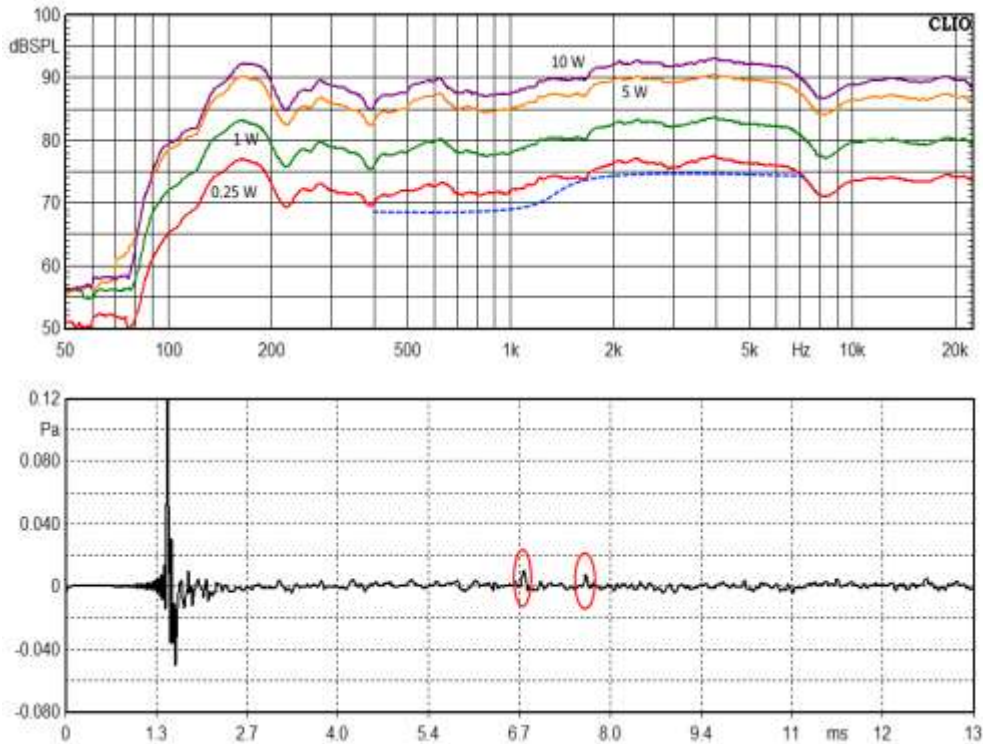
**Figure 7. Comparison of measured and simulated system impedance.**

Near-field SPL of the driver and PR was measured and compared to simulation as depicted in Fig. 8.



**Figure 8. Near-field response of driver and PR comparing measurement with simulation.**

On-axis SPL for various input power levels was measured, and can be seen in Fig. 9.



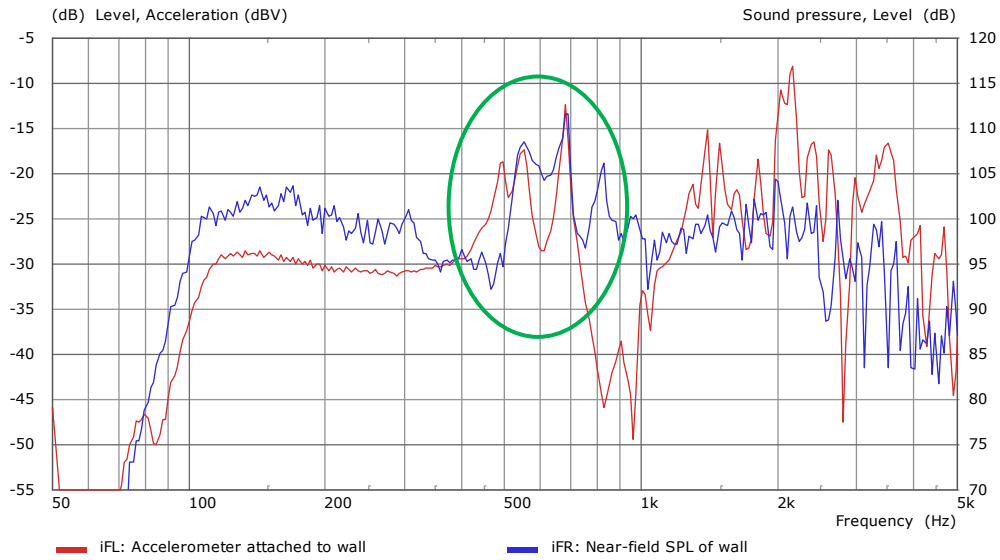
**Figure 9: Top: 1/3-octave on-axis 1m SPL for various input powers. Bottom: Impulse response.**

Since the input signal was LogChirp, the driver under test was not driven in to power compression scenario. As can be seen, SPL over 90 dB/1W/1m was measured, very close to the linear prediction yet in contrast to around 85 dB predicted by worst case non-linear simulation. The trend of baffle step as illustrated by a blue dash curve (in Fig. 9) is clearly seen. The bump between 100 Hz to 200 Hz was due to the floor and ceiling reflections. Note time-gate was not enabled in this graph. Reflection from floor and ceiling are circled in the impulse response.

The boxes were made of ABS material. The side wall thickness is 3 mm whereas 6 mm is employed for front and back plates. Thicker front and back plates were used to minimize the strongest vibrations, as they occur on the faces where the driver and PR are mounted. Internal standing waves and wall vibrations will create coloration impairing sonic clarity.

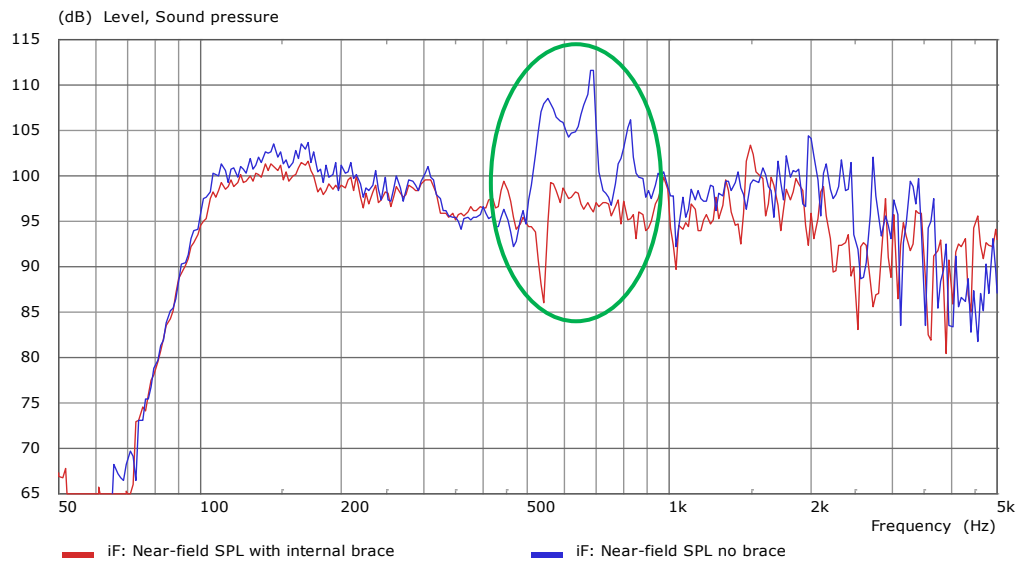
Near-field SPL of the wall is illustrated in Fig. 10. The data closely agreed with the output of an accelerometer attached to the wall. The green circled region shows the most critical vibrations occurring in the midrange output of the system.





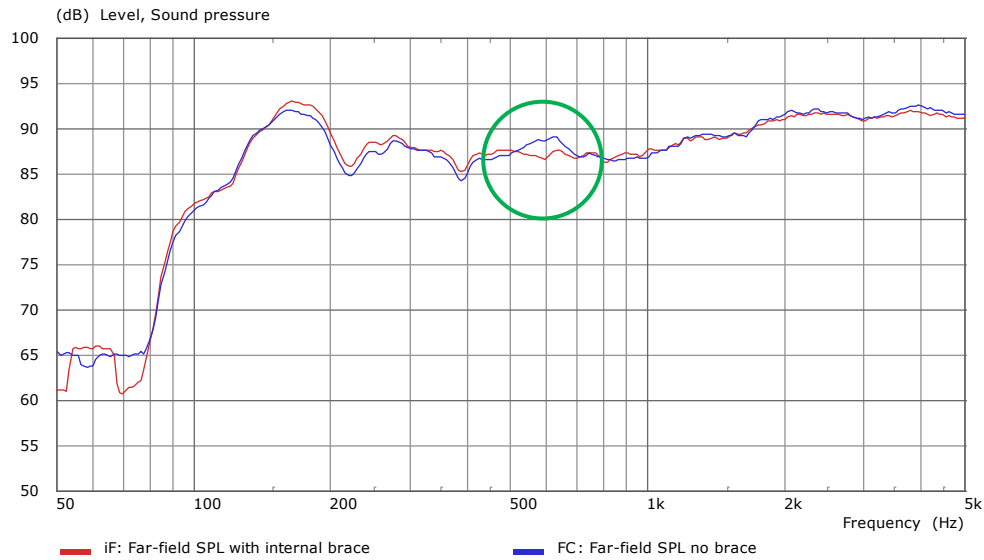
**Figure 10. Wall vibration measured by accelerometer and near-field SPL of side wall.**

To minimize the undesired wall vibration, an internal brace was added to the box. From near-field SPL measured in Fig. 11a, it can be seen the brace was effectively alleviating wall vibrations.



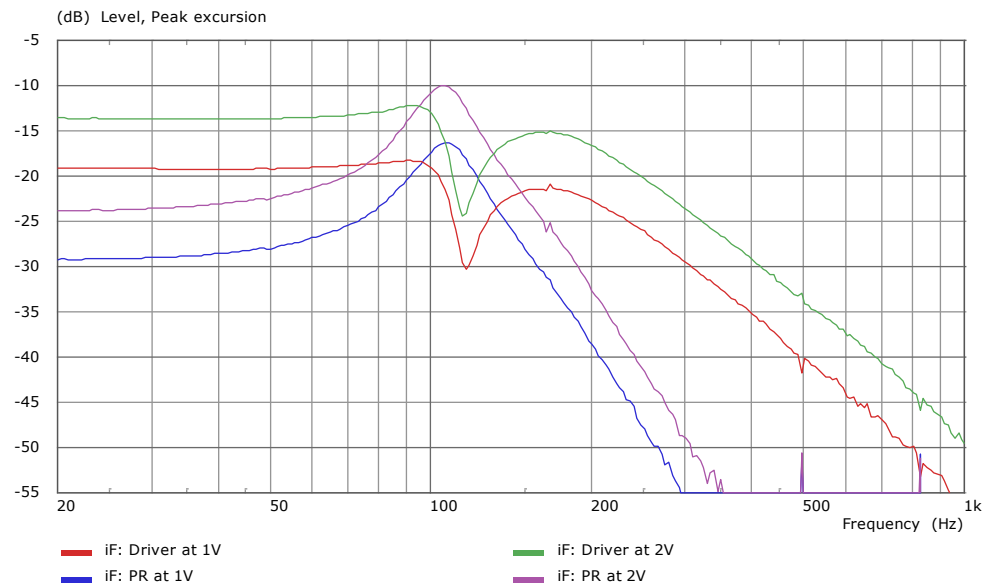
**Figure 11a. Near-field measurement of side wall showing effect of brace.**

The effect is also clearly observed in the far-field measurement shown in figure 11b.



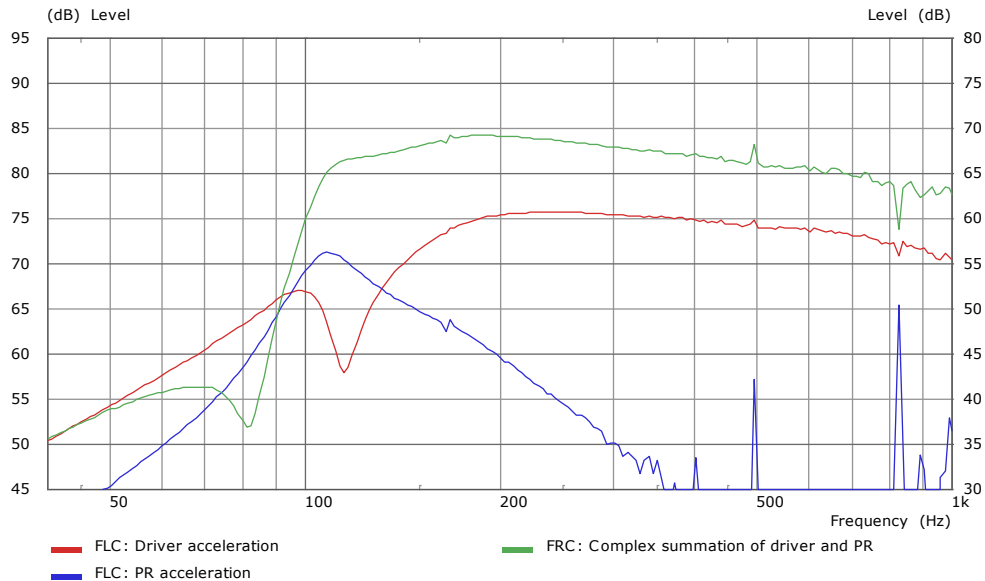
**Figure 11b. Far-field measurement of loudspeaker showing effect of brace.**

The laser displacement sensor was also used to measure excursion of the driver and PR (Fig. 12).



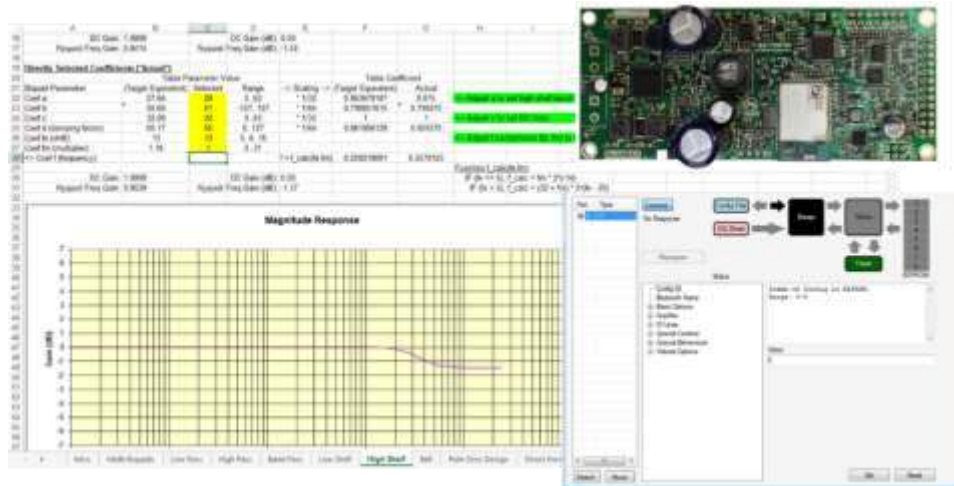
**Figure 12. Driver and PR peak excursion level for different input levels. Sensitivity of the laser sensor is 0.25V/mm.**

Based on the excursion data, we can readily obtain acceleration of the driver and PR for predicting piston SPL as shown in Fig. 13 (SPL is proportional to diaphragm acceleration). This is an indirect way to accurately observe low-frequency response in the absence of an anechoic chamber. It can be seen by comparing figures 3 & 13 that the prototype bass alignment and simulation give quite close agreement.



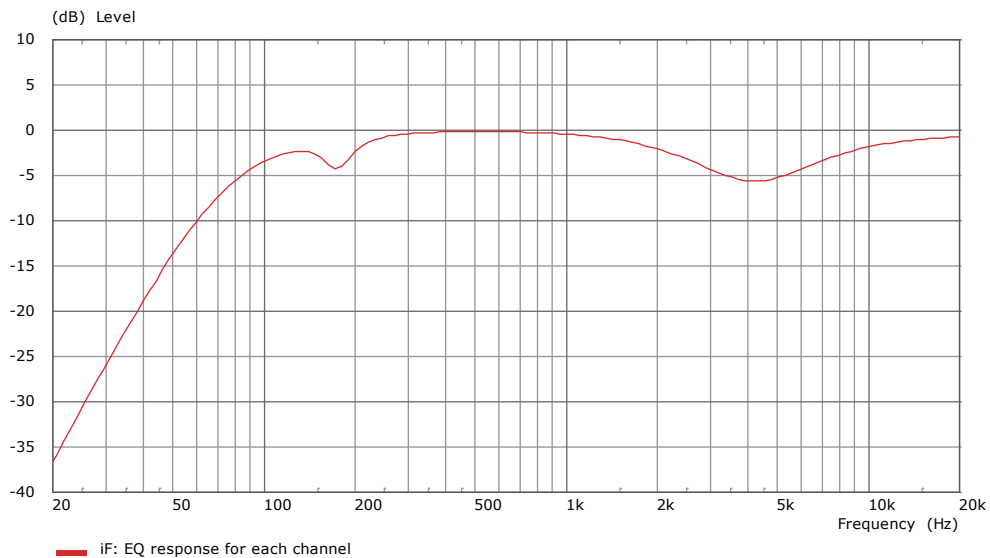
**Figure 13: SPL predicted from laser excursion measurement of driver and PR.**

Tectonic’s wireless amplifier module (TEAM-DBA3-301) was used to provide equalization. The amplifier has sixteen fully-programmable digital biquad filters. Design of the filter is done in an Excel spreadsheet as shown in Fig. 14. A high-shelf filter, as shown in the figure, was used to address the baffle step. A band-stop filter was used to alleviate the low-frequency bump due to reflection and system Q. There were additional tweaks to contour the mid-high frequency band to give a pleasing balance with different types of music.



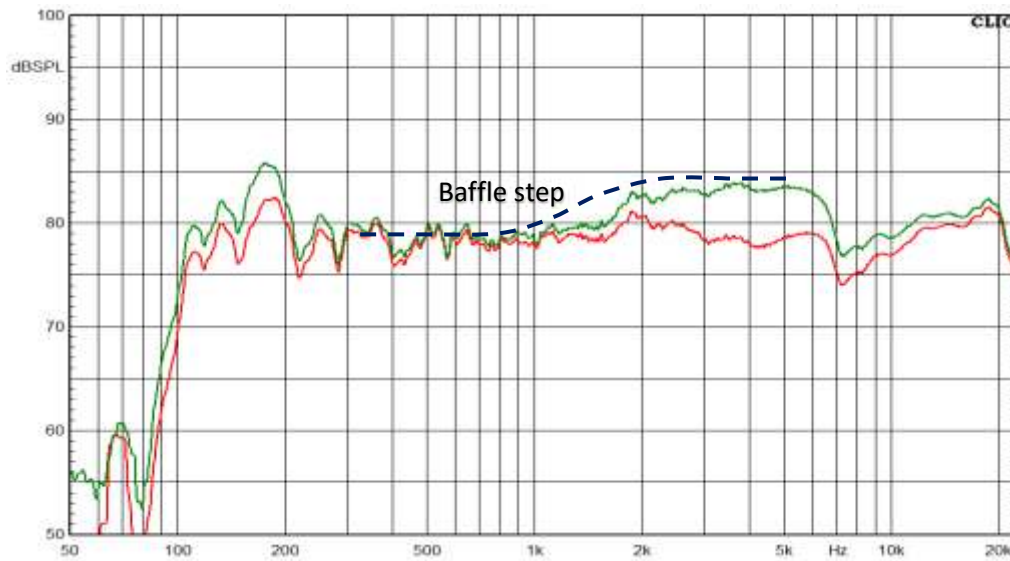
**Figure 14. TEAM-DBA3-301 wireless amplifier module and its software for EQ and downloading settings.**

The final equalization response is depicted in Fig. 15. Coefficients of filters were obtained by the spreadsheet and downloaded to the amplifier board by the communication software “Bongo”.



**Figure 15. Equalization frequency response.**

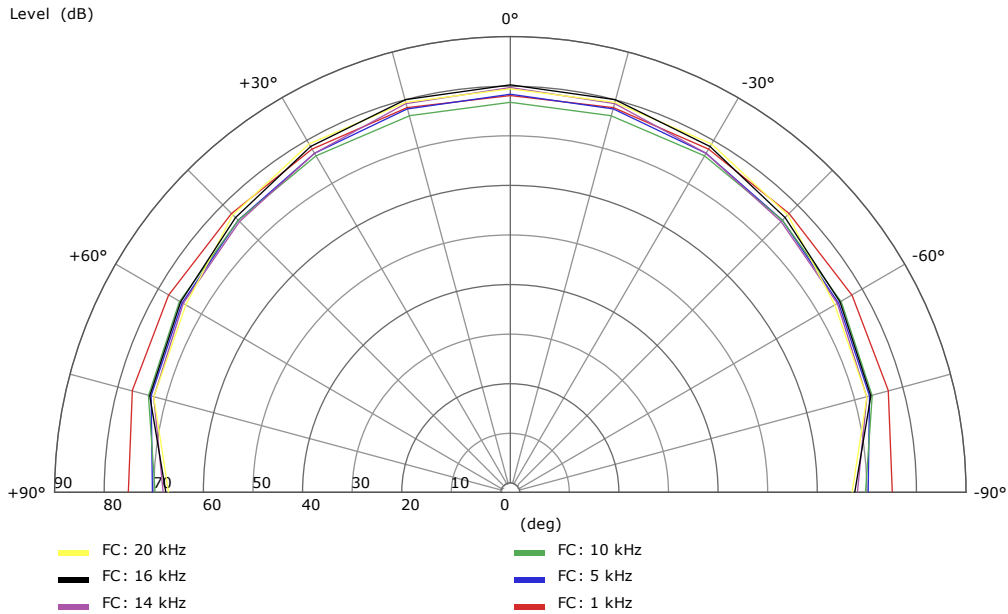
Far-field SPL before and after applying the EQ is shown in Fig. 16. The speaker was on top of a tripod. Sound absorbing materials were used to minimize reflections. Please contact Tectonic directly for further information on the TEAX-DBA3-301 amplifier module.



**Figure 16. Far-field measurement of speaker without EQ (green) and with EQ (red); 1/3-octave smoothed. The dashed line shows the predicted baffle step response.**

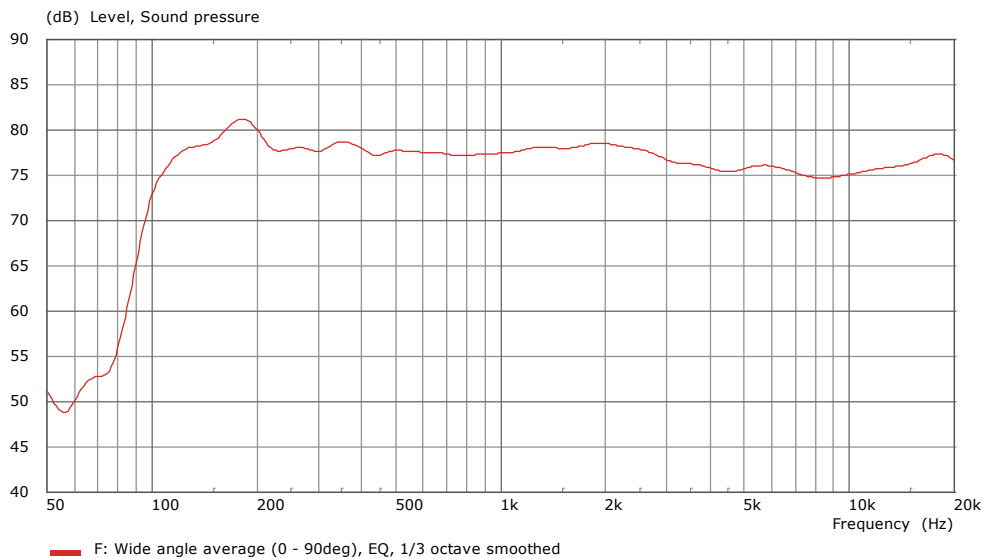
On-axis response on its own does not provide sufficient information to assess real listening experience. Making multiple measurements in different spatial locations is important to better understand the true acoustic radiation into a room. During EQ tuning, on-axis, off-axis (horizontal, vertical) and quasi-ground plane measurements were conducted. If a notch or bump appears in all the measurements, it is likely necessary to use an EQ stage to address it. We also need to measure at multiple signal levels to establish an appropriate Q, gain and bandwidth of an EQ stage. In general, high Q stage should be avoided.

Polar response of the speaker is shown in Fig. 17. Top plate of the tripod was rotated to make off-axis angles from 0 to 90 degrees in 15 degrees step. It can be seen the speaker has excellent off-axis performance. Wide and smooth spatial dispersion is maintained beyond 16 kHz.



**Figure 17. Polar response of the prototype.**

Wide-angle-averaged response is illustrated in Fig. 18. The curve compared with a single on-axis SPL provides better understanding of a speaker performing in real listening environments. These two figures clearly demonstrate the advantages of Tectonic’s BMR technology: full-range and wide-dispersion performance.



**Figure 18: Wide-angle averaged response (0° – 90°)**

**CONCLUSIONS AND SUMMARY**

This application note outlines the steps of developing an enclosure with PR for the TEBM35C10-4 BMR driver. In order to achieve smooth low-frequency response, parameters of passive radiator were carefully tuned in the design stage. In addition, the enclosure dimension was specifically chosen to diminish impairments of box modes. Test data of an actual driver and passive radiator were fed to simulation to improve accuracy.

Baffle-step compensation and minor tweaks at certain bands to improve sonic performance were taken care with equalization implemented on the DSP of an amplifier module.

Polar response, wide-angle-average response and on-axis response were measured to provide a comprehensive assessment of the prototype.

For additional information on acoustic simulations based around your specific requirements, PR design and manufacture, please contact Tectonic Elements ([sales@tectonicelements.com](mailto:sales@tectonicelements.com)) or your local representative.

### Appendix

#### Appendix 1

Detailed dimensions of the 600 cc enclosure are shown in the following figures.

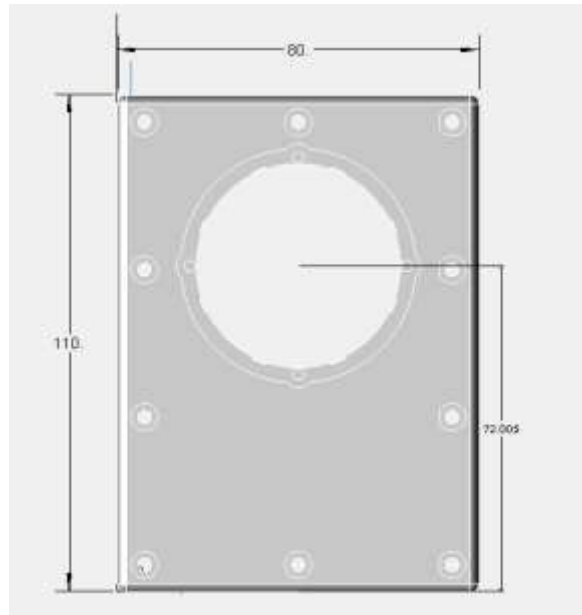


Figure 19. Front-baffle dimensions (mm).

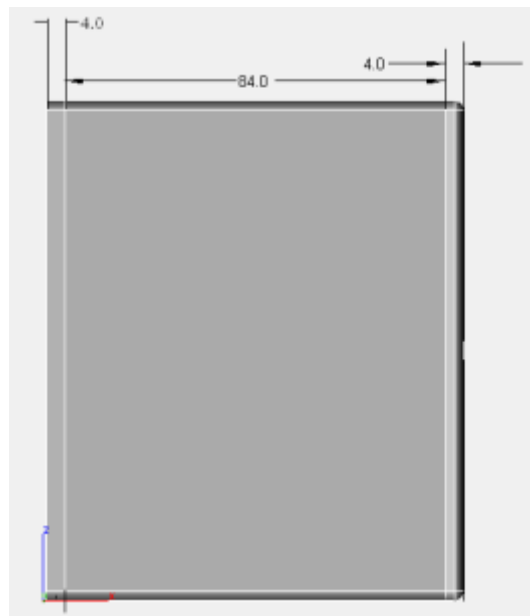


Figure 20. Side-wall dimensions (wall thickness 3 mm).



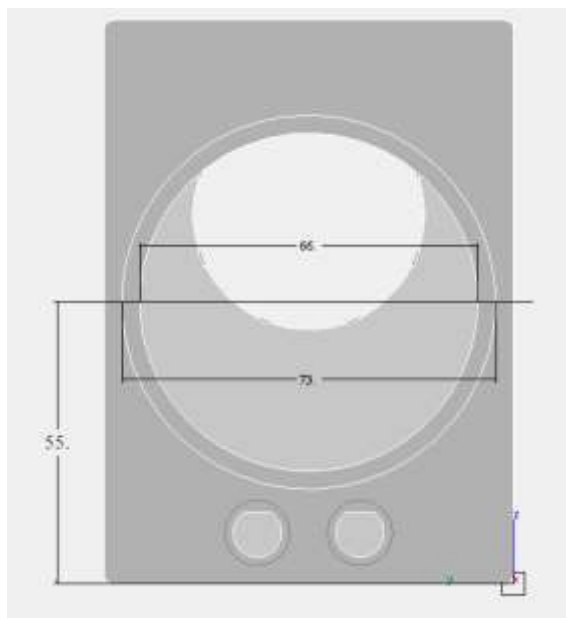


Figure 21. Back-baffle dimensions (mm).