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Investigations on the Influence of Speaker Enclosure Material on Performance Characteristics of Speakers

Authors: Raajdeep Kaur[1], Amey Chavan[2]

[1] Aditya Birla world academy, India; [2] On My Own Technology (OMOTEC), Mumbai, India

Email: kaurraajdeep3@gmail.com, a.chavan @omotec.in

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Abstract. While there are many factors influencing the quality of sound and immersive audio experience, the material enclosure plays a vital role in shaping overall sound quality. The function of a speaker enclosure is to provide structural strength and protection to the transducers, vibration and resonance control, internal damping, and aesthetics to the audio system. The current experimental study explores different materials that can be utilized to make speaker enclosures and their effects on audio performance. Enclosures made of MDF, regular plywood, marine plywood, Baltic birch plywood, and 3D-printed material were tested. The performance of the speaker was evaluated by measuring the frequency response and sensitivity by varying input power, resistance, and enclosure material. Experiments were designed and executed according to Taguchi's L9 OA. In order to obtain the optimized combination, ANOVA analysis was performed.

I. INTRODUCTION

The speakers are the devices that convert electrical signals into audible sound. A typical speaker system is made up of high-frequency and low-frequency drivers, speaker enclosure and additional components such as crossover circuits, which greatly influence the performance. A speaker enclosure serves a number of important tasks such as housing the driver units, controlling resonance and vibrations, preventing undesired cancellations of sound waves from the front and rear of the diaphragm, and influencing the system's overall tonal character and efficiency. Baltic birch, ordinary plywood, marine-grade plywood, Medium Density Fiberboard (MDF), and even modern alternatives like 3D-printed polymers are commonly used materials. The mechanical and acoustic properties of different enclosure body materials, such as density, stiffness, damping coefficient, and surface texture, influence how sound waves move through the enclosure, bounce off of it, and are absorbed. [1] This study explores the influence of different enclosure materials on important speaker performance parameters, such as Speaker pressure level is desired to be maximum for a given input. Taguchi's L9 orthogonal array approach was applied while developing the test conditions to methodologically change the resistance, input power, and enclosure material. The relevance of each component is then determined, and the finest blend for desired output is found, through ANOVA. This study intends to assist in making better judgments in loudspeaker development by experimenting with acoustic impacts of enclosure materials.

1.1 Low Frequency driver: A cone made of fiber or thick paper is attached to the voice coil. The voice coil is assembled in the ferrite magnet. When the signal is supplied to the driver, the coil generates linear back-and-forth movement, depending on the intensity of the signal amplitude. Accordingly, the cone also moves the surrounding air, generating low-frequency sound waves.[1]

(a) Mid speaker magnet side **(b) Mid speaker cone side**

Fig. 1: Mid speaker: magnet side and cone side

1.2 High Frequency driver: Tweeters are high-frequency drivers in loudspeakers that reproduce high-frequency sounds above 20,000 Hz. Tweeters use very light, small, and fast-moving diaphragms to reproduce high-frequency waveforms. They are generally smaller in size compared to low frequency drivers, though the construction and working is similar. [1] Fig. 2 (a) indicates the high frequency driver of Penza audio make, model 4401 of capacity 60 watts. The Driver was attached to aluminum flair of throat size 1" diameter as shown in fig. 2 (b). Metal flairs are extensively used in high-power applications. They also ensure better strength, consistent sound directivity, reduce undesired vibrations, and contribute to cleaner sound at higher SPL.

(a) High Frequency Driver **(b) 6 X 7 Metal flair front**

Fig. 2: High Frequency Driver and 6×7 Metal Flare Front.

1.3 Passive Cross-Over Network: The necessity of all multi-driver loudspeakers includes the functions of a crossover network designed to send the different bands of frequencies to the proper drivers (woofer, midrange, and tweeter). The passive crossover network functions without any active components such as power supply and utilizes components like resistors, inductors and capacitors. [3]

1.4 Amplifier An audio amplifier is a type of electronic device that is set up to boost the amplitude of low-power premium audio signals coming from microphones, musical instruments, or audio players. Such low-level premium audio signals need to be increased before they can be supplied to loudspeakers to generate sound. The system plays a vital role in modern audio equipment, professional or otherwise, along with the rest of the components of the system, in ensuring proper sound fidelity, dynamic range, and adequate loudspeaker sound pressure level. [1] Fig. 3 shows a 500-watt power amplifier used to power the sound system.

Fig. 3: Power Amplifier

1.5 Digital Mixer: An electronic device used to combine, process, and control various audio signals in the digital domain is called a digital audio mixer, sometimes referred to as a digital mixing console. Digital mixers transform incoming analogue signals into digital form, process them using digital signal processing (DSP) algorithms, and then transform them back into analogue signals for output, in contrast to analogue mixers, which work with continuous electrical waveforms. [1] Fig. 4 indicates Digital mixer used for conducting the experiments for the study.

Fig. 4: Digital Crossover

1.6 Speaker Enclosure: A wooden sound enclosure is a structural housing that influences the system's acoustic performance while supporting and containing loudspeaker drivers. These enclosures, which are made mostly of wood or engineered wood materials like particleboard, plywood, or medium-density fiberboard (MDF), have both mechanical and acoustic purposes. An ideal enclosure material provides structural security to electronic audio components while reducing undesired vibrations.[4] [5] Fig. 5 (a) indicates 8" speaker cabinets made in commercial south make ply. It is softer in nature, good to machine and light in weight. Fig. 5 (b) indicates a cabinet made in marine ply, which is also called hardwood. It is heavier in weight and least affected by moisture. Fig. 6 (a) indicates the cabinet made in MDF material. It is slightly lighter in weight compared to marine cabinets. In the audio industry, it is the most used material due to its ability to provide better tone of sound for low power sound applications. Also it is economical compared to other materials. Fig. 6 (b) indicates a cabinet made from Baltic Birch ply. This material is extensively used in high power professional audio systems. The top layer of ply is softer and ductile in nature. Therefore, it can provide better resonance than marine play.

(a) Cabinet in Commercial ply **(b) Cabinet in Marine ply**

Fig. 5: Cabinets made from Commercial and Marine ply

(a) **Cabinet in MDF** **(b) Cabinet in Birch ply**

Fig. 7 shows the typical dimensions of the cabinet used for conducting the experimental study. The cabinet was made from 12 mm thickness ply. The front baffle was machined for mounting the speaker, metal flair and air pass. The

cabinet was made in trapezoidal V shape. It means the back is smaller than the front to reduce the undesired effect of standing waves.

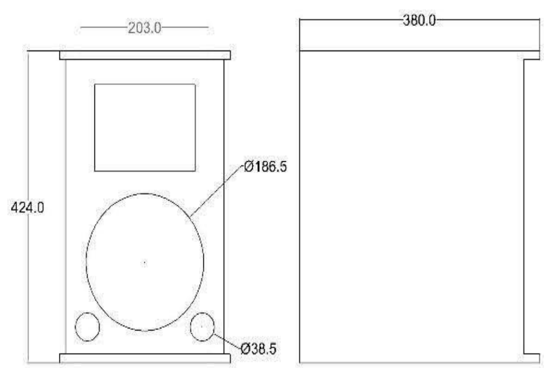


Fig. 7: Typical Design of Speaker cabinet used for experiment.

1.7 Foam: 1.7.1 Acoustic cotton wool: The primary purpose of acoustic cotton wool in speaker enclosures is to improve performance and absorb sound. Sound waves produced by the driver cone's rear side bounce around and produce reflections inside a speaker box. Distortion may result from these reflections reentering the cone and interfering with the sound output."Boxy" or hollow noises may be produced by vibrations within the enclosure. [6] These resonances are reduced with cotton wool, producing a softer, more organic sound. The acoustic cotton wool is shown in fig. 8.

Fig. 8: Acoustic cotton wool

1.7.2 Egg tray type Foam: The primary use of egg-tray type foam in speaker enclosures is acoustic treatment. Its porous structure and distinctively uneven surface contribute to the enclosure's improved sound quality. The irregular "eggcrate" surface disperses sound waves in various directions, in contrast to flat foam. It performs well acoustically without adding a lot of weight. The egg-tray foam is shown in Fig. 9.

Fig. 9: Egg tray foam

Experiment Details: For experimentation, the factors selected were speaker cabinet material, foam condition, and amplification factor, as shown in Table 1. There are several performance metrics available for sound systems, such as frequency response, speaker pressure level, directivity, sensitivity, distortion, impedance and dynamic range. For this experiment, Speaker pressure level and frequency response were selected as response variables. [7], [8] The selected performance metrics can be influenced by type of speaker cabinet material, due to its property of resonance and ability to absorb the vibrations. Further, Foam insulation materials are used to reduce the diffraction and unwanted echoes. Amplification factor was controlled through the digital mixer, where input in dB was varied from 0 to -20 range at fader. Input from the Amplifier was kept at 75 %. Speaker pressure level and frequency response were measured using an RTA mic placed 20 ft away. Table 1. Factors and levels selected for Experiment.

Table 1: Factors and levels for cabinet material, foam, and amplification input.

Levels	Factors		
	Cabinet Material	**Foam**	**Amplification Input (dB)**
1	Commercial ply	No Foam	0
2	Marine ply	Single white foam	-5
3	Birch ply	Double white foam	-10
4	MDF	Egg tray foam	-20

According to No. of factor and levels identified, L16 orthogonal array was used to plan the experiments, as shown in table 1. L16 Orthogonal array allows 4 levels and 5 factors for designing the experiments. Experiments were designed using the L16 orthogonal array as shown in table 2.

Table 2: L16 orthogonal array with responses

Ex. No.	Cabinet Material	Foam Condition	Amplification Factor	Cabinet Material (coded)	Foam Condition (coded)	Amplification Factor (coded)
1	Commercial ply	No Foam	0	1	1	0
2	Commercial ply	Single white foam	-5	1	2	-5
3	Commercial ply	Double White foam	-10	1	3	-10
4	Commercial ply	Egg tray foam	-20	1	4	-20
5	Marine ply	No Foam	-5	2	1	-5
6	Marine ply	Single white foam	0	2	2	0
7	Marine ply	Double White foam	-20	2	3	-20
8	Marine ply	Egg tray foam	-10	2	4	-10
9	Birch ply	No Foam	-10	3	1	-10
10	Birch ply	Single white foam	-20	3	2	-20
11	Birch ply	Double White foam	0	3	3	0
12	Birch ply	Egg tray foam	-5	3	4	-5
13	MDF	No Foam	-20	4	1	-20
14	MDF	Single white foam	-10	4	2	-10
15	MDF	Double White foam	-5	4	3	-5
16	MDF	Egg tray foam	0	4	4	0

During the experiment, speaker pressure level and frequency response values for High frequency driver and Mid frequency Driver were measured with RTA Mic as shown in table 2.

Results and discussions:

3.1 ANOVA Analysis of Variance (ANOVA) is a statistical method used to determine whether there are significant differences among the means of three or more groups. It partitions the overall variability in the data into components attributable to different sources: between-group variation and within-group variation. By comparing the ratio of these variances using the F-test, ANOVA identifies whether the observed differences in means are statistically significant or due to chance. It is widely applied in experimental research for hypothesis testing, factor comparison, and optimization studies. Speaker Pressure level is desired to be maximum for the given input, hence for ANOVA of HF and Mid speaker "Larger the better" criteria was used. For frequency response, the "Nominal the better" criterion was used [9]. Signal to noise Ratio for larger the better is given by:

Signal to noise Ratio for larger the better is given by:

$$\frac{S}{N} = -10 \quad \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}$$

(1) Where , n – no. of observations in trial , yi observed response value for the ithtrial. Signal to noise ratio for Nominal the better is given by,

$$\frac{S}{N} = 10 \quad \frac{y^2}{\sigma^2}$$

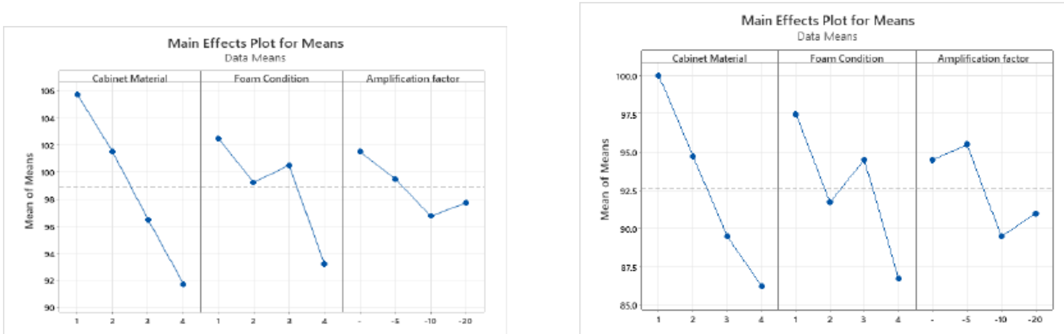
(2)Where, μ = mean of observed responses, σ = variance of observed responses.

3.2 ANOVA for SPL HF Table 3. Indicates the ANOVA of Speaker pressure level for High frequency transducer.

Table 3: Analysis of Variance for Means

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Cabinet Material	3	442.25	442.25	147.417	22.68	0.001	61.11
Foam Condition	3	190.25	190.25	63.417	9.76	0.01	26.29
Amplification factor	3	52.25	52.25	17.417	2.68	0.141	7.22
Residual Error	6	39	39	6.5			5.39
Total	15	723.75	723.75				100.00

In Table 3, the ANOVA of SPL HF shows that, of all the factors, cabinet material has the biggest impact on speaker pressure level, which can be explained by its capacity to control air movement and reduce resonance. Additionally, foam condition contributes about 26%. In contrast, the amplification factor has very little effect on speaker pressure level.



Main effect plot for speaker level for HF (b) Main effect plot for speaker level for Mi

Fig. 10: Main effect plots of speaker level for HF and Mid frequencies.

The impact of cabinet material, foam condition, and amplification factor on the response variable is depicted in the main effects plot in fig.10 (a). With a sharp drop in mean response from 106 dB to 92 dB, cabinet material was shown to be the most important aspect, demonstrating its dominance in system performance. Egg tray foam produced a considerable decrease in reaction, indicating that it is less desirable than the single white, double white, and no-foam conditions, which showed relatively little difference. The reaction decreased up to -10 and then stabilized, indicating a moderate, non-linear effect of the amplification factor. Overall, the findings show that performance is most affected by cabinet material choice, which is followed by foam condition and amplification factor.

- ANOVA of SPL Mid : Table 4. Indicates the ANOVA of Speaker pressure level for Mid frequency transducer.

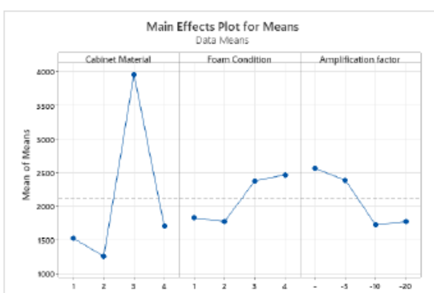
(b)

Analysis of Variance for Means							
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Cabinet Material	3	437.25	437.25	145.75	15.76	0.003	52.07
Foam Condition	3	250.25	250.25	83.417	9.02	0.012	29.80
Amplification Factor	3	96.75	96.75	32.25	3.49	0.09	11.52
Residual Error	6	55.5	55.5	9.25			6.61
Total	15	839.75	839.75				**100.00**

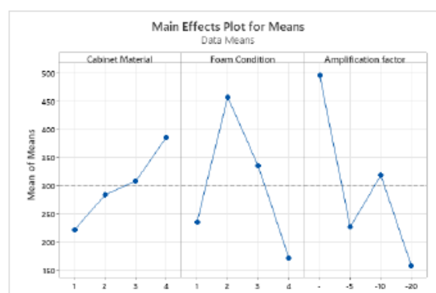
Cabinet material is the most significant factor, accounting for 52.07% of the overall variation in the answer, according to the analysis of variance (ANOVA) results in Table 4. Additionally, the foam condition had a noteworthy impact, accounting for 29.80% of the total. The amplification factor was the least significant and contributed a smaller percentage of 11.52%. Overall, the findings suggest that the foam condition and cabinet material had the most effects on the system response, whereas the amplification factor had a negligible, nonsignificant impact. Fig. 10 (b) Main effect plot for speaker level for Mid. With a steady drop in response from 100 dB to 86 dB, cabinet material has the largest effect and plays a major part in performance variation. The foam condition has a moderate effect; the double white foam condition and the no foam condition had stronger reactions (about 95 dB and 98 dB, respectively), while the foam with the egg-tray type caused a noticeable decrease (about 87 dB). The amplification factor has a non-linear trend, with a minor improvement in responsiveness from 0 to -5, a severe decline at -10, and a partial recovery at -20. According to these trends, the most important parameters influencing system output are foam condition and cabinet material, with amplification factor having a minor but significant impact. 3.4 ANOVA of Frequency Response for HF Table 5. ANOVA of Frequency Response for HF

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Cabinet Material	3	18581097	18581097	6193699	24.37	0.001	77.90217
Foam Condition	3	1572532	1572532	524177	2.06	0.207	6.592919
Amplification Factor	3	2173453	2173453	724484	2.85	0.127	9.11231
Residual Error	6	1524752	1524752	254125			6.392599
Total	15	23851834					**100**

According to Table 5, analysis of variance (ANOVA) results, cabinet material accounts for 77.90% of the total variation, making it the most important factor determining the response. On the other hand, the amplification factor and foam condition each contributed 9.11% and 6.59% of the variation, respectively. Overall, the results highlight that the most important component influencing system performance is cabinet material, with foam condition and amplification factor having relatively little, statistically irrelevant effects.



(a) Main effect plot for speaker level for HF



(b) Main effect plot for speaker level for Mid

Fig. 11: Main effect plots for speaker level at high (HF) and mid (Mid) frequencies.

Fig. 11 (a) shows main effect plot for Frequency response HF. With material 3 generating a significantly greater mean reaction than the other materials, which stay comparatively lower and closer in magnitude, the data show that cabinet material has the most noticeable influence. Material 3 appears to be the best choice for improving performance based on this steep peak. The foam condition, on the other hand, shows a moderate influence, with means progressively rising from condition 1 to condition 4, suggesting that better foam properties positively impact the reaction, albeit not as significantly as cabinet material. With the highest mean at factor -5 and a slow decline at -10 and -20, the amplification factor exhibits a non-linear pattern, underscoring the idea that excessive amplification impairs performance. Overall, the plot indicates that the most important component affecting the system response is cabinet material, with foam condition and amplification factor making significant but minor contributions to performance improvement.

3.5 ANOVA of Frequency response for Mid Table 6.ANOVA for Frequency response for Mid

Analysis of Variance for Means							
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Cabinet Material	3	55233	55233	18411	0.39	0.762	7.08
Foam Condition	3	18590	18590	61997	1.33	0.351	23.84
Amplification Factor	3	25822	25822	86073	1.84	0.24	33.10
Residual Error	6	28064	28064	46774			35.97
Total	15	78008					**100**

According to Table 6, analysis of variance (ANOVA) results, the amplification factor accounted for 33.10% of the variation, followed by foam condition (23.84%) and cabinet material (7.08%). Overall, the results show that the experimental parameters under study did not have significant or statistically significant effects under the investigated settings, even though the amplification factor and foam condition account for a small amount of variability. Fig. 11 (b) indicates the main effect plot for frequency response Mid. It is clear from the figure that cabinet material has a progressive influence, with material 4 producing the best performance and the mean reaction rising gradually from material 1 to material 4. The choice of foam has a substantial impact on system performance, as evidenced by the more noticeable fluctuation in the foam condition, with condition 2 generating the highest mean response, followed by a reduction at condition 3, and a dramatic decline at condition 4. Among the three variables, the amplification factor exhibits the most significant effect; the highest mean is found at factor level -5, while the lowest mean is found at extreme values like -20, indicating that amplification needs to be carefully calibrated to prevent performance loss. While all three elements affect the response, the plot shows that foam condition and amplification factor exhibit the most changes, indicating their crucial significance in system optimization.

Conclusion

With a focus on sound pressure level and frequency response, this study examined how enclosure material, foam condition, and amplification factor affect loudspeaker performance. ANOVA offered statistical insight into the significance of the factor effects, while the experimental design, which was based on Taguchi's L16 orthogonal array, allowed for a systematic evaluation of them. The findings consistently showed that cabinet material is the most important component, having a significant impact on frequency response and sound pressure level because of its function in vibration damping and resonance management. By absorbing internal reflections, the foam condition was also found to be important, significantly enhancing mid-frequency performance. The amplification factor, on the other hand, only displayed a mild, non-linear effect that was not statistically significant. Overall, the results show how crucial it is to carefully choose the enclosure materials for loudspeaker design as they have a direct impact on tonal accuracy and acoustic performance. The study also demonstrates how acoustic treatments, including interior foam lining, improve performance by reducing standing waves and distortion. In order to achieve better sound quality in consumer and professional audio applications, these insights offer a solid foundation for optimizing enclosure design and material selection.

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