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Published in:
Proceedings of the 142nd Audio Engineering Convention Convention

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Juul-Nyholm, H. B., Severinsen, J. C., Schneider, H., Mortensen, N. H., & Andersen, M. A. E. (2017). Construction of Lightweight Loudspeaker Enclosures. In *Proceedings of the 142nd Audio Engineering Convention Convention* Article 9784 Audio Engineering Society.

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Audio Engineering Society Convention Paper

Presented at the 142nd Convention
2017 May 20–23, Berlin, Germany

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Construction of Lightweight Loudspeaker Enclosures

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ABSTRACT

On the basis of bass cabinets, this paper deals with the problem of reducing loudspeaker enclosure weight. An introductory market analysis emphasizes that lighter cabinets are sought, but maintenance of sound quality is vital. The problem is challenged through experiments and simulations in COMSOL Multiphysics, which indicate that weight reduction and sound quality maintenance is possible by reducing wall thickness and using adequate bracing and lining.

1 Introduction

In recent years, the weight and size of loudspeakers has been reduced significantly and many portable loudspeakers of varying quality has entered the audio market. In the music industry the manufacturers of sound reinforcement systems have also introduced lighter and more transportable amplifiers and cabinets. The lightweight cabinets without integrated amplifiers for bass reinforcement weigh between 9 and 15 kg and might, in spite of their appealing title, cause both trouble and back problems for touring musicians.

Earlier, the amplifier, whether it is integrated or not, contributed much to the weight, but the efficiency of amplifiers has increased and thereby the weight has been reduced [1] [2] [3]. Today, the two main contributors to the cabinet weight is the magnet of the loudspeaker driver and the construction of the enclosure.

Cabinet enclosures has been built of thick wooden plates for several decades in order to elude undesirable coloring of the reproduced sound. The coloring is

caused by vibrations in the enclosure walls due to both structural and acoustic excitation from the driver. Tappan [4], Iverson [5], Stevens [6], and Barlow [7] all describe how cabinet resonances behave and can be made insignificant by choice of shape, material and bracing. Backman [8] has investigated vibrations in conventional enclosure materials and the possibilities of damping them with different vibration-damping sheets. Bastyr and Capone [9] has investigated the effect of internal bracing in a standard production loudspeaker using a scanning laser Doppler vibrometer and a computational BEM model. The literature agrees that low frequencies, especially the fundamental frequencies of the enclosure walls, has the greatest influence on the sound coloring from flat walls of several reasons: All parts of the wall are moving in the same direction in the fundamental mode whereas different parts of the wall are moving in opposite directions in higher order modes. These modes are also difficult for the uniform pressure in the enclosure to excite. In addition, the high frequencies are more directional and will not influence the sound of the driver as much as the low, omnidi-

rectional frequencies. As Tappan [4] put it in 1962, *"thick or heavy walls are not always necessary for high quality,"* but the problem of significantly reducing the enclosure weight does not seem to have been a priority for either the industry or the academic research.

The work described in this paper challenges the conventional construction of cabinet enclosures with the objective of creating initial guidelines for weight reduction of cabinet constructions and maintained sound quality. The objectives are pursued through a market analysis, experiments with a market reference and a test cabinet, and modelling in COMSOL Multiphysics. During the experiments, sound quality and resonances were evaluated through measurements of the frequency response of the full loudspeaker system and through listening tests. The COMSOL simulations were conducted in order to display the displacement patterns of the cabinet walls, to investigate the effect of wall thickness and bracing and to validate the method for future optimization prior to physical experiments.

2 Market Analysis

A series of interviews were conducted in order to identify user needs and characterize the use of bass cabinets. Those interviewed were three dealers of bass equipment and six bass players of different age and ambition. A majority of them agreed that weight and portability are important but should not be achieved at the expense of sound quality. The bass players all had experience with moving heavy gear from rehearsal to venue, and while some had bought new, lighter cabinets or amplifiers, others had developed a habit of borrowing amplification from other bassists' playing at the venue simply to avoid hauling their own heavy gear. Beside the weight and sound quality, bassists seemed to prefer amplification gear with a neutral, but staging appearance and the possibility of angling the driver up towards the bassist's ears.

In addition to the interviews, a benchmarking of bass cabinets with 12" drivers were conducted through comparison of the lightest models of ten commercial bass amplification brands, including the market reference of this paper. The ten cabinets weighed between 10.9 and 17.5 kg and all had a volume between 58 and 99 liters. The cost of the cabinets ranged from 336 to 1078 USD (March 9th 2017) and no correlation between price and weight was observed. All the cabinets were primarily build from plywood plates and the main reason for

the price differences is probably choice of electronic features and not least choice of driver.

3 Enclosure Tests

3.1 Test Setup

The market reference cabinet has an approximated internal volume of $0.320\text{ m} \times 0.320\text{ m} \times 0.438\text{ m} = 0.045\text{ m}^3$, is built from 18 mm plywood, and weighs 14 kg. The driver is a ceramic Eminence driver of 12" and the cabinet has a bass reflex vent. Based on the market reference a test cabinet was built and through continuous comparison of perceived sound quality and frequency responses to the market reference, the test cabinet was rebuilt and improved aiming at an acceptable performance for the analyzed market.

Measurements of the frequency response were conducted in an anechoic chamber. A microphone was placed in front of the center of the loudspeaker driver at a distance of 1 m and connected to a portable PC. On the PC the Room EQ Wizard program (REW) was used to send a sine sweep of 1 W through an amplifier to the cabinet loudspeaker and record the emitted sound in Sound Pressure Level (SPL). The frequency range was limited from 20 to 4500 Hz. This was based on the understanding that the transition from bass driver to tweeter occurs at 3500 Hz and the argument that low frequencies have a much higher impact on enclosure sound emission than high frequencies [4].

The main parameter to be altered in the experiments was the wall thickness. The volume would be an obvious parameter for weight reduction, but as the volume has a huge impact on the cabinet's ability to reproduce bass frequencies [10], this parameter was held constant. The test cabinet was built with inner dimensions, electronics and vent as the market reference. The differences in the frequency responses and the perceived sound quality could be used to illustrate the influence of the enclosure construction, because the only difference between the cabinets was their construction. The test cabinet was assembled with intertwining edges and wood glue in 6 mm MDF and sealed with acrylic sealant and rubber strips. The weight of this cabinet was 7.8 kg.

3.2 Test Results

It was expected that reducing the wall thickness would affect the sound quality of the cabinet. This can also be seen in Fig. 1, where the frequency response of the test cabinet is compared to the frequency response of the market reference. Both the market reference and the test cabinet have the characteristic boost of the vent, but from 120 Hz to the transition from the bass driver to the tweeter at 3400 Hz the frequency response of the test cabinet has several peaks and dips which distinguishes the two curves. The effect of the wall thickness reduction was also obvious in the listening test, where the test cabinet sounded weak and muddy compared to the market reference.

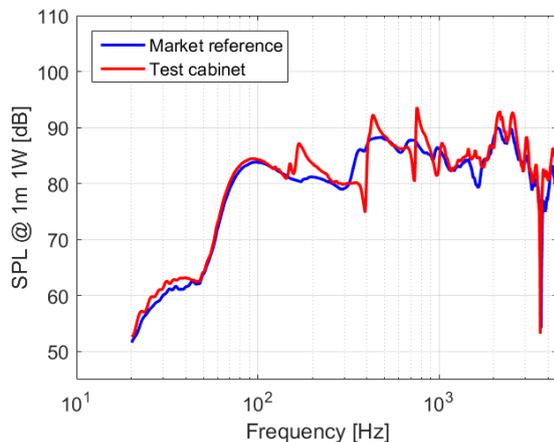


Fig. 1: Comparison of frequency response for market reference and test cabinet.

According to Bastyr and Capone [9], peaks can be ascribed to in-phase vibrations of the driver and one or more walls resulting in an increased sound output. Inversely, dips can be ascribed to the walls and driver moving out of phase resulting in a damping of the emitted sound. This might be the cause of the observed peaks at 170 Hz. Wall damping might also be inadequate as light tapping on the walls reveals a series of hollow sounds readily excitable in the construction. Wall frequencies are observed in the frequency response at 400 Hz and 740 Hz, exposed by the characteristic reduction before and increase after forming an S turned on the side as described for vented enclosures by Tappan [4].

The first improvement of the test cabinet was achieved with damping of standing waves and sound emissions

from the back of the cone to the walls through lining with acoustic foam. This resulted in a test cabinet weight of 8.4 kg. Comparison of the improved frequency response and the market reference response can be seen in Fig. 2. The resonance S'es was clearly damped by the lining, but not the peak at 170 Hz. Although the improvement was audible, it did not make the test cabinet comparable to the well-defined and pure bass sound of the market reference.

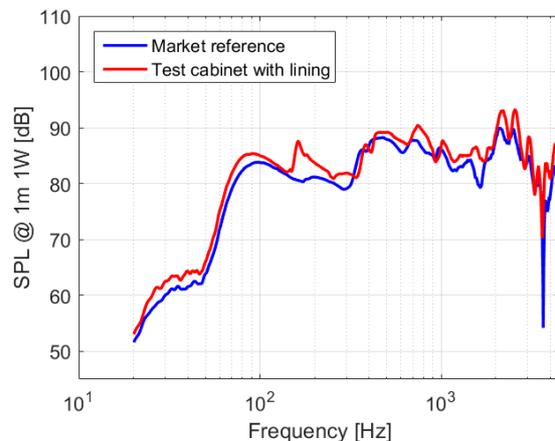


Fig. 2: Comparison of frequency response for market reference and test cabinet with lining.

Next, a perpendicular brace between the centers of the cabinet side walls was introduced to alter the fundamental resonance in the two biggest surfaces. The test cabinet weight was increased to 8.7 kg. The effect on the measured frequency response can be seen in Fig. 3. The peak at 170 Hz seems to have been reduced and moved to 110 Hz by the brace and in the range from 240 to 1300 Hz the test cabinet response is almost coinciding with the response of the market reference. The test cabinet still sounded weak compared to the market reference, but the muddy part of the sound was attenuated.

Finally, the test cabinet was rebuilt to include both lining, perpendicular bracing and 22 triangular braces glued to the inner corners of the enclosure. Comparison of the frequency response of this version of the cabinet and the market reference can be seen in Fig. 4. The peak at 110 Hz has been damped to the level of the market reference curve like the rest of the response of the test cabinet and the sound quality was further improved. A series of blind listening tests were conducted with this version of the test cabinet. The two cabinets were

placed behind a curtain with four other loudspeakers of different use and a test sound piece was played on each loudspeaker in turn. As the audience did not know the order or the appearance of the loudspeakers they could blindly grade them from the perceived sound production. Some of the 15 test persons described differences in the sound of the test cabinet and the reference cabinet, but they were equally graded and the conclusion of the listening test was that the sound of test cabinet is comparable to a commercially produced bass cabinet.

The test cabinet's final construction weighed 9.9 kg. This is a reduction of 29% from the 14 kg of market reference. The weight includes the 4.2 kg driver and additional spare parts of 2.1 kg, which has not been the focus of the work. The weight of the cabinet construction alone has been reduced with 53% from 7.7 kg to 3.6 kg.

In Fig. 5 an illustration of the different versions of the cabinet.

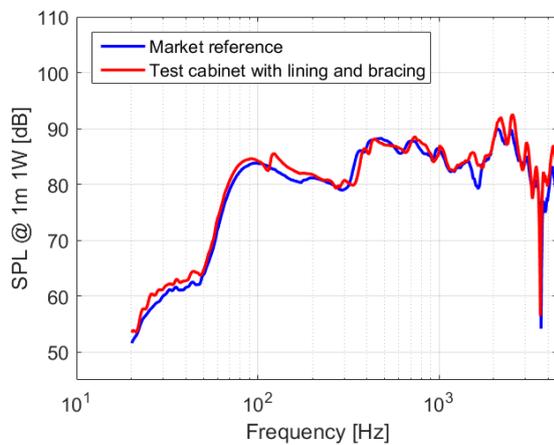


Fig. 3: Comparison of frequency response for market reference and test cabinet with lining and perpendicular bracing.

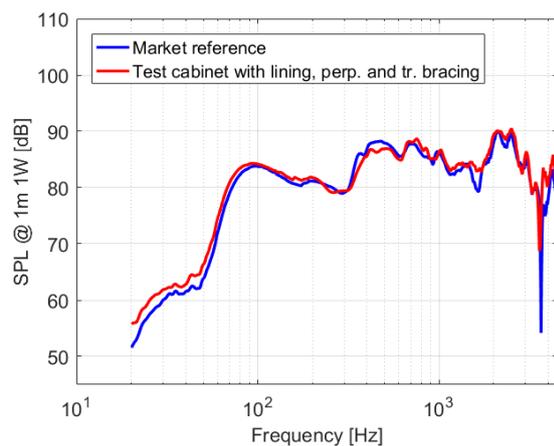


Fig. 4: Comparison of frequency response for market reference and test cabinet with lining, and perpendicular and triangular bracing.

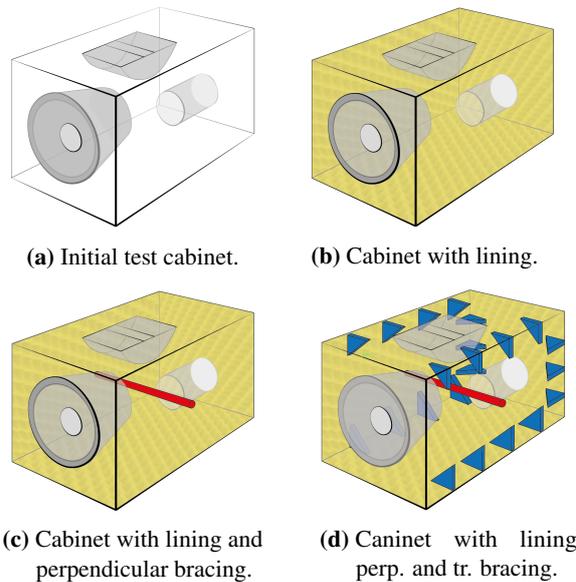


Fig. 5: The four different versions of the test cabinet.

4 COMSOL Simulations

4.1 Model Setup

The correlation between frequency response and wall displacements, and the effect of wall thickness and bracing was investigated with a vibroacoustic model in COMSOL Multiphysics. The model was set up in the Pressure Acoustics Module, the Solid Mechanics Module and the Electric Circuit Module with inspiration from COMSOL Tutorials [11] [12]. The following assumptions were used to simplify the model:

- The cabinet is symmetrical in two directions and does not have handle or electronics.
- The driver can be modelled as a membrane moving as a function of the Thiele-Small parameters of the driver used in the market reference.
- The two cabinet side walls have the material properties: $\rho = 867 \text{ kg/m}^3$ (measured from the panel used to build the test cabinet), $E = 4 \times 10^9 \text{ Pa}$ and $\nu = 0.25$ (estimated from [13] and [14]).
- The four remaining walls are rigid and sound-proof.
- The inductance of the voice coil is constant.
- The cabinet is placed in an anechoic chamber.

The geometry, as seen in Fig. 6, was drawn as a quarter of a rectangular box with dimensions as the test cabinet, one fourth of a center-placed rear wall vent and a quarter circle membrane due to the assumptions. Surrounding the box was a quarter sphere representing the air.

The outer layers of the quarter sphere was defined as a perfectly matched layer (PML) in the Pressure Acoustics Module, which enable modelling of farfield and frequency response. The two-axis symmetry for the air domain was also defined as well as the normal velocity of the membrane, u_D , and the sound hard barrier property of the cabinet walls.

The cabinet wall under investigation was the only domain assigned to the Solid Mechanics Module. Its symmetry, clamped boundary condition and the fixation from the investigated braces was set.

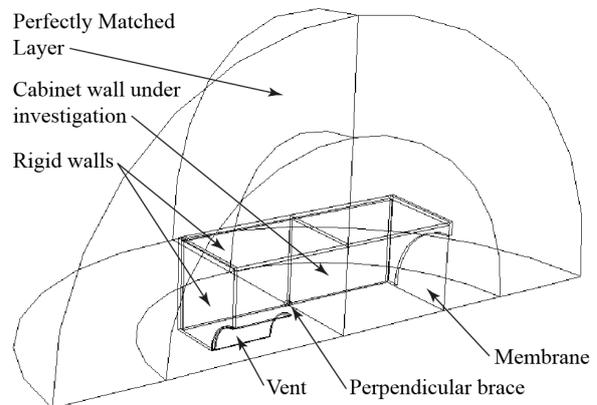


Fig. 6: 3D model in COMSOL Multiphysics representing one fourth of the simplified test cabinet.

The Electric Circuit Module was used to model the loudspeaker driver using the equivalent circuit of the electrical and mechanical parts of the loudspeaker as seen in Fig. 7. The symbols refer to the Thiele-Small parameters. The Thiele-Small parameters of the 12" driver from the market reference was measured using a Klippel Analyzer.

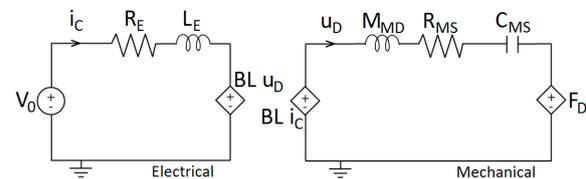


Fig. 7: Circuit model for the electrical and mechanical parts of the loudspeaker [11].

The mesh was designed to evaluate the wall displacements by sweeping a triangular mesh through the wall. The inner air domain was meshed with tetrahedrals and its surface mesh was swept out through the PML. The maximum mesh size was chosen so that one wavelength in air at any modelled frequency had at least six elements.

Models of 6, 9, 12, 15, and 18 mm walls were evaluated in addition to models of 6 mm walls with a perpendicular rod corresponding to the one from the experiments and a lengthwise brace as advocated by Tappan [4]. Each model was run with 200 frequencies logarithmically distributed between 10 and 4000 Hz and took approximately 2 hours to run with a fully coupled solver

and the use of 3.4 GB physical memory and 5.2 GB virtual memory.

4.2 Simulation Results

The frequency response of the model with unbraced 6 mm walls and the model with 6 mm walls and perpendicular bracing can be seen in Fig. 8. The perpendicular brace seems to affect the response from 90 to 400 Hz. The first significant peaks and dips of the unbraced wall are equalized and a new peak occurs at 300 Hz.

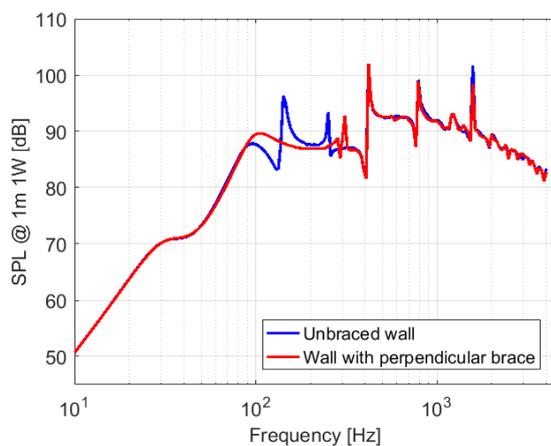


Fig. 8: Comparison of modelled frequency response of two walls without bracing and two walls with perpendicular bracing.

Three selected displacement plots, corresponding to the frequencies of the three peaks in the affected range, can be seen in Fig. 9. At 141 Hz a fundamental mode can be seen in the unbraced wall with a displacement above 0.1 mm. The braced wall is not visibly moving at this scale. A second order mode can be observed at 250 Hz, where two areas are moving in opposite directions. Again, the braced wall is stationary compared to the unbraced wall. At 309 Hz the displacement of the braced wall is in phase and much bigger than that of the unbraced wall, which is moving in antiphase. The perpendicular brace seems to have generated a resonance at this frequency. As expected, the biggest displacements occur at frequencies with SPL peaks.

In Fig. 10 the frequency response of models with different wall thicknesses and the model with 6 mm walls and lengthwise brace are plotted from 70 to 4000 Hz. From 10 to 70 Hz the curves are coinciding without the offset. With increasing wall thickness the peaks between

the resonance frequencies are reduced and moved to higher frequencies until they are eliminated at 18 mm thickness. A simulation of the sound output of the wall could be interesting in order to determine whether the peaks are actually reduced or simply damped in the direction of the driver due to the increased frequency at which they are excited. The frequency response of the lengthwise brace resembles the response of the 18 mm wall. Moreover, the peak at 1500 Hz is lower for the braced wall than for any of the unbraced walls.

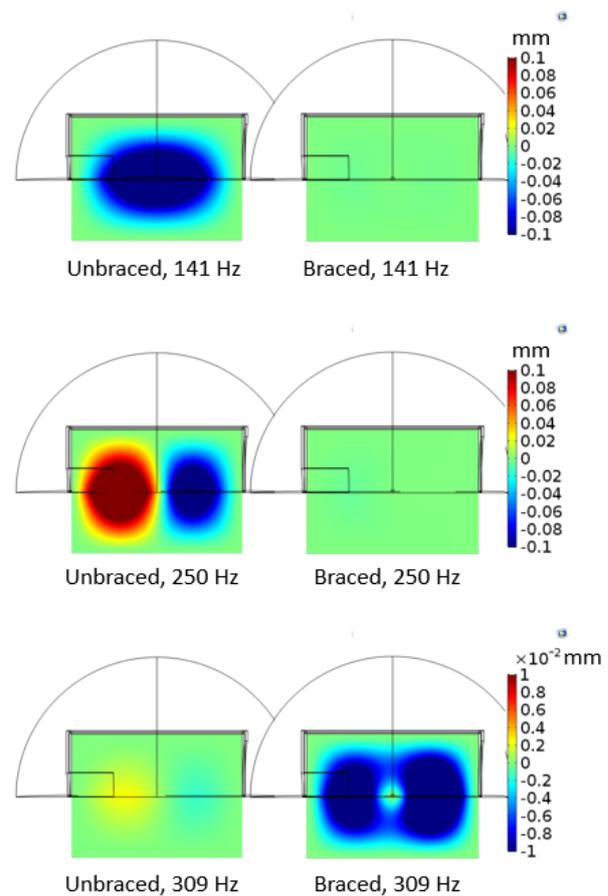


Fig. 9: Maximum displacements of 6 mm wall unbraced and with perpendicular bracing. Notice that the plots for 309 Hz has a different scale.

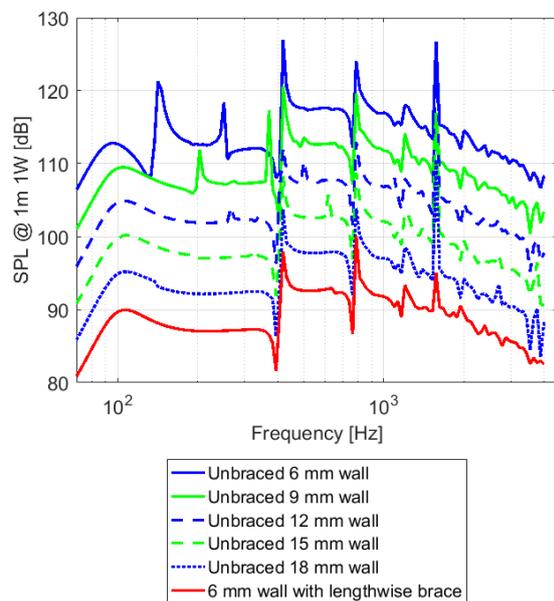


Fig. 10: Frequency response of models with varying wall thickness and model with lengthwise brace. The curves are mutually offset with 5 dB.

4.3 Verification of the Model

In Fig. 11 the measured and modelled frequency response is plotted. The modelled values are plotted with an offset of -5.5 dB. The curves have multiple similarities; a boost from the vent at 90 Hz followed by a peak, a dip closely followed by a peak around 400 Hz and a dip closely followed by a peak around 750 Hz. Above 900 Hz no similarities are observed. The peaks of the COMSOL model have more defined points compared to the measured ones. The differences are most likely caused by assumptions of material properties and the assumption that only the two biggest walls of the cabinet contribute to the sound coloring. It is very likely that the less pointy tendency of the measured curve and the M-shape just above 2000 Hz is caused by the resonances of the rest of the cabinet.

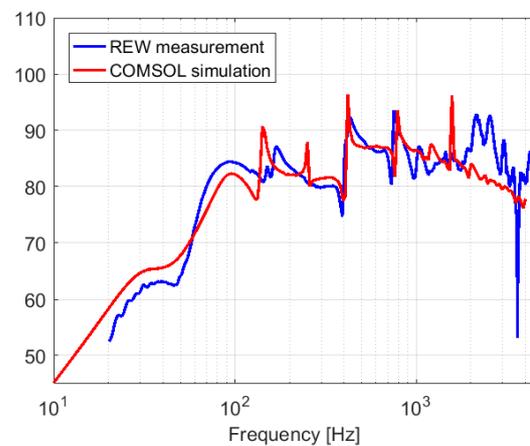


Fig. 11: Comparison of frequency response of cabinets without lining and bracing measured with REW and simulated with Comsol Multiphysics.

5 Discussion

The market analysis indicated that bass players seek lighter cabinets but not at the expense of sound quality. This justifies the work of this paper, where a combination of frequency response and listening tests is used for indicating the sound quality of reference and test cabinet. The frequency response makes measurement and comparison of the cabinets easy, but does not provide insight into the structural dynamics of the enclosure or the perceived sound. While both simulations and stepwise alterations of the test enclosure are used for identifying the causes of the observed peaks and dips, listening tests connect the measurements to the live experience of the cabinet.

The tests have shown how acoustic foam can smooth the frequency curve at resonance S-shapes and how bracing can reduce peaks and move them from one frequency to another. Furthermore, the tests have shown that a cabinet with a 53% reduced enclosure weight can maintain a sound quality comparable to a market reference.

The simulations have given insight into the effect of bracing both with regard to structural displacements and the frequency response. The effect of the lengthwise brace compared to increasing wall thickness should be emphasized as crucial for weight reduction

of enclosures. Comparison of the experiments and simulations suggest that the peaks between the S-shapes are caused by wall vibration, because they can be altered by wall thickness and bracing. On the other hand, the S-shapes seems to be caused by standing waves, as they were significantly reduced by lining the test cabinet with acoustic foam.

The work gives rise to reduction of the other parts of the cabinet, particularly the driver, as the driver was responsible for 40% of the weight of the test cabinet in its final construction. For further reduction of cabinet weight, designers are encouraged to avoid symmetry, damp standing waves with absorbent material, challenge cabinet shape as well as panel materials, and last but not least use adequate bracing to reduce wall thickness.

6 Summary

The problem of lighter cabinets and sound quality maintenance has been investigated through experiments with a test cabinet and a market reference and through simulations with COMSOL Multiphysics. The experiments and simulations have illustrated the influence of the construction of the enclosure. Clamped 6 mm walls gave a weak sound and a frequency response with many dips and peaks. Lining and bracing improved the sound quality to be comparable to the market reference with a notable weight reduction of 29% for the total bass cabinet and 53% for the enclosure construction alone. More specifically, the lining reduced the S-shaped peaks, which was not affected by wall thickness, which indicates that the S-shaped peaks were caused by standing waves. Bracing altered both the height of the peaks between the S-shapes and the frequency at which they occurred. The simulation of lengthwise bracing was particularly interesting, as the frequency response of this model was comparable to the model with 18 mm walls. The lengthwise brace, or other tools for minimizing free square wall areas, are essential for significant weight reduction together with adequate lining.

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