New automotive audio system architectures based on central push-push subwoofer

Marc-Olivier Chauveau[1], Marc Levasseur[2],

1: Moca audio, 56 rue de suède, 37100 Tours, France
2: Marlev, 1 rue de la paix, 38000 Grenoble, France

Abstract: This paper describes a new sound system architecture based on a compact subwoofer box using two speakers in a push-push arrangement located in a central position in the car cabin, directly cross-overed with midranges/fullranges (with no door woofers). This solution brings many advantages on different aspects like sound quality of low frequencies reproduction, packaging, privacy, vibrations compared to existing conventional sound system architecture. It is also scalable in order to address all system level performances. We will describe and illustrate the different benefits, system architecture possibilities, measurements, and comparison with the conventional approach. We will also describe the challenges and ways to optimize such architectures from a loudspeaker and acoustical point of view.

Keywords: sound system architecture, push-push subwoofer, y0 subwoofer

1. Introduction

Since decades automotive sound system architectures have not much evolved regarding low frequencies reproduction, principally due to integration constraints: they are based on woofers integrated inside the doors. These woofers are cross-overed whether directly to tweeters (for cheaper systems), or to midranges/tweeters (for higher level systems), sometimes extended with a subwoofer located in the trunk (for premium systems). This type of architecture brings a lot of problems for the bass reproduction because of the asymmetry of the listening position, ending up with major phase problems. It is also usually related to non negligible rattling problems.

We can now see a trend in the industry, where OEMs are wanting to remove these door woofers for the following benefits:

- More storage space
- Simplified door design (less cabling, simplified carrier plate design, no rattling)
- Improved privacy (doorwoofers are causing a lot of leakage towards the outside of the cabin)

Furthermore the Electric Vehicles boom brings new opportunities for sound system architectures, in particular because there is no more gearbox transmission needed. As a result, we now have in such vehicles more space available in the central console.

Hence the opportunity to rethink sound system architectures and benefit from the EV revolution!

2. Central push-push subwoofer architecture

2.1 Description

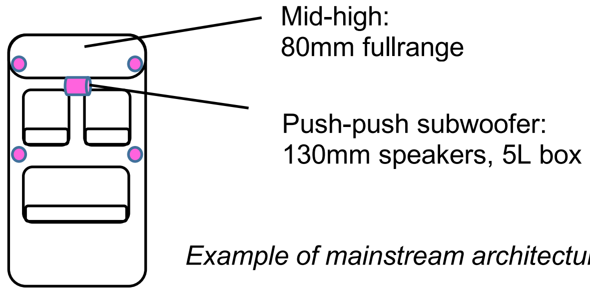
We considered the following aspects in our approach to re-think sound system architectures:

- Compacity
- Scalability
- Simplicity
- Improve bass reproduction quality
- Eliminate vibration/rattling problems
- No woofers inside the doors (and ultimately no need for a subwoofer)

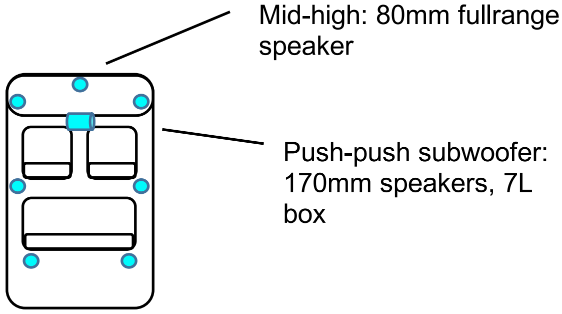
We ended up with a solution using a compact subwoofer box with two speakers in a push-push arrangement located in the central console. This solution helps improving the bass reproduction as the source is located on the y-symmetry axis of the car, we therefore have no more phase problems. Compared to a subwoofer located in the trunk we also obtain a better acoustic coupling to the room as it is not exciting so much the room eigenfrequencies. Moreover the push-push configuration does not produce any external vibration.

This subwoofer should then be cross-overed directly to midranges/fullranges speakers.

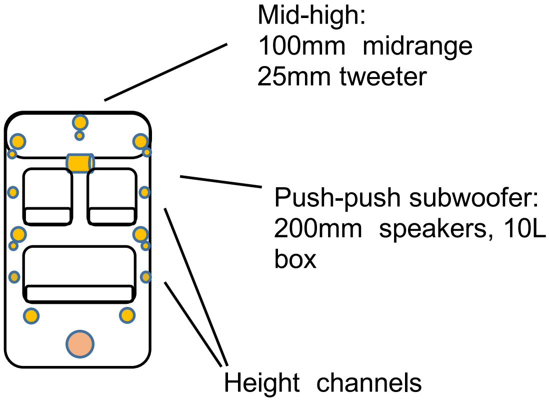
This architecture is scalable from mainstream up to high-end levels. Here are some application examples:



Example of mainstream architecture



Example of hifi system



Example of high-end system

2.2 Push-Push configuration

The principle of a push-push arrangement is to have two speakers in a box being back to back (or front to front), playing in phase. The two speakers can share the same air volume, or have two independent air volumes. The big advantage of such disposition is to cancel almost completely the vibrations. Following the 3rd Newton law, when a membrane moves (a force is applied to it) it creates a reaction force on the box that makes it move towards the opposite direction.

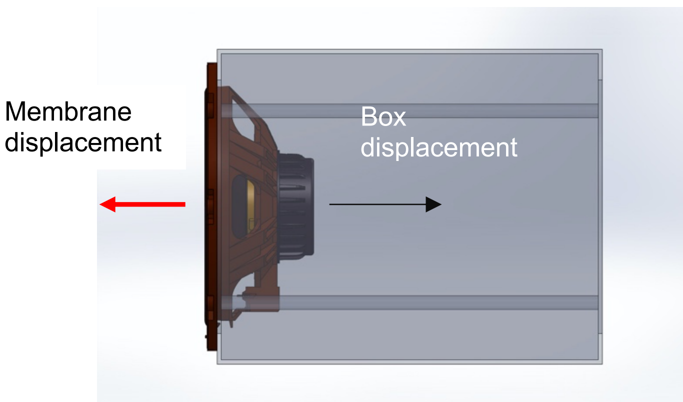


fig 1: Classical single speaker subwoofer

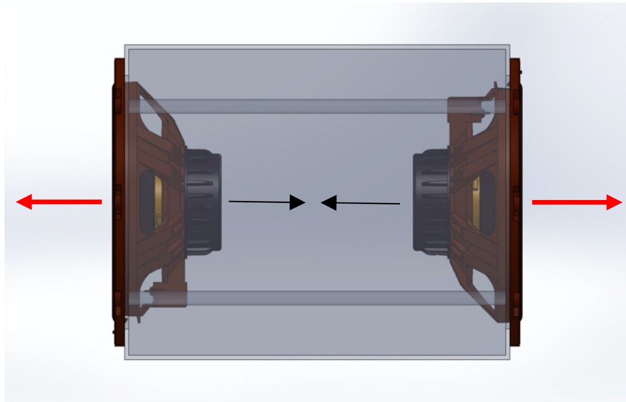


Fig 2: Push-push subwoofer

With a push-push arrangement the reaction forces are cancelling each other. This vibration cancelling effect has two advantages:

- From a sound quality perspective, having no vibration of the box helps getting a dryer bass (no ringing effect from the box)
- No vibration of the box means no transmition to other surrounding mechanical parts , which could create rattle

3. Acoustic benefits of this audio architecture

3.1 Acoustic coupling of the subwoofer with the car cabin

We have seen that one of our top priority requirements was to be as compact as possible: the space available in a car is very limited.

Having two loudspeakers in a small closed volume ends up with a pretty high resonance frequency (typically around 70-90hz). And the frequency response of such a closed box is usually following a high-pass slope of 12dB/oct below the resonance frequency, so typically in the bandwidth where we need to use it! Hopefully if we locate our box in the central console we benefit from a good acoustic coupling with the car cabin, bringing a substantial gain in this frequency range.

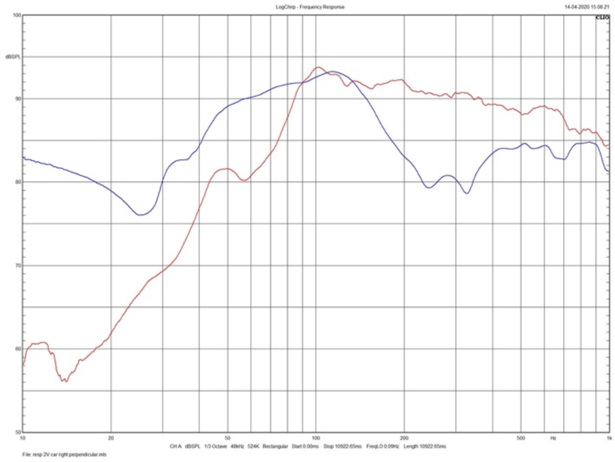


Fig 3: Push-Push subwoofer 2x130mm in 5L SPL
Red curve= on infinite baffle
Blue curve= in car central console

We can reach up to +15dB gain at 20Hz and about +10dB on average below 80Hz.

Furthermore we are not exciting too much the room eigenfrequencies in this location. This results in a smoother frequency response compared to a trunk subwoofer.

3.2 Bass repartition

Another acoustic benefit of this new bass topology is that we obtain a much better bass repartition throughout the cabin with only one sound source. The frequency response curve of the push-push subwoofer is very similar between front and rear seats compared to a trunk subwoofer. Also, as mentioned previously, we have no more delay problems compared to door woofers solutions (where left and right door woofers have different arrival times at every seat) and which are causing major phase problems.

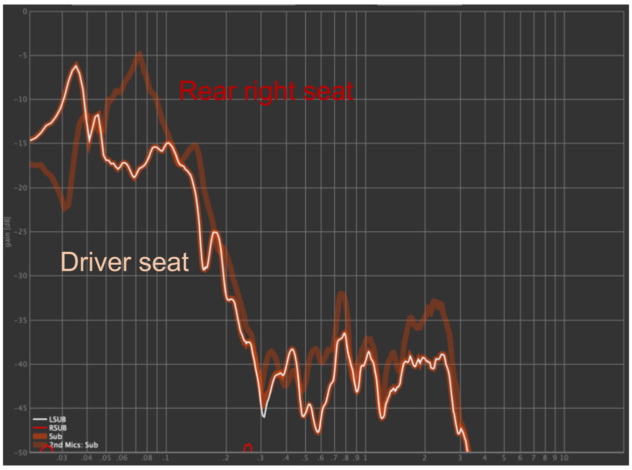


Fig 4: Usual trunk subwoofer SPL @driver and rear right seat

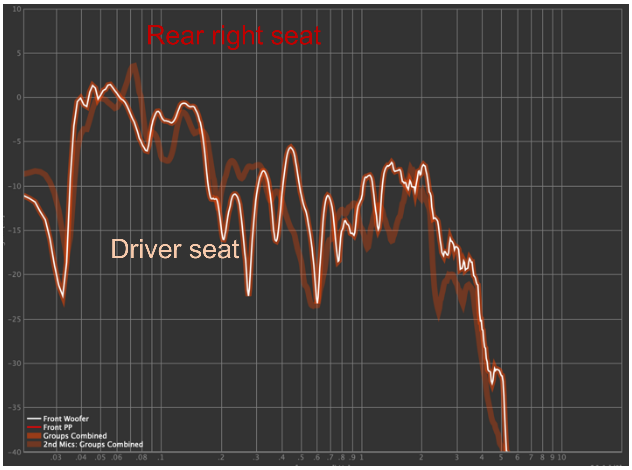


Fig 5: Door woofers SPL @driver and rear right seat

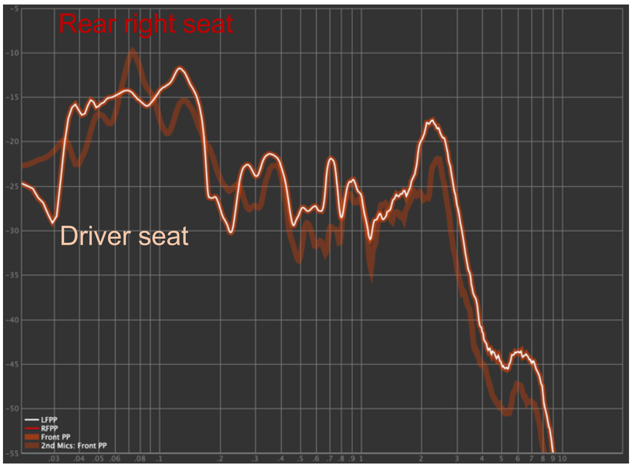


Fig 6: Central push-push subwoofer SPL @driver and rear right seat

We can observe that we get a more even bass distribution between all seats with the central push-push compared to a trunk subwoofer. With a trunk subwoofer we have significant variations between front and rear seats with up to 15dB differences. These differences are very hard to manage through tuning in order to get a more even repartition.

Also peaks and dips due to room modes are much smoother with the central push-push as it is less exciting the room eigenfrequencies due to its location.

Door woofers have a very similar bass repartition compared to the central push-push but we will see later that other aspects of the sound quality are less than optimum.

3.3 Direct sound and reverberation approach

It is also interesting to consider the comparison between direct and reverberant sound in order to evaluate sound intelligibility. It is well known and studied that reverberant sound negatively impacts the musical sound quality[1]. When the reverberation is too important, we get a “bathroom” effect which is unwanted for high fidelity sound reproduction. Here we have to consider the ratio:

$$\frac{direct\ sound}{direct\ sound + reverberant\ sound} \qquad [1]$$

Ideally this ratio should be equal to 1 (like in free field or recording studio). If this ratio is >1 this means the reverberant sound is reaching a similar or upper level than direct sound and in opposite phase. If this ratio is <1 this means reverberant sound is reaching a similar or upper level than direct sound. In both cases the situation is unwanted to achieve clear sound reproduction. On top of that, reverberant sound should be as low as possible, and so maximizing the direct sound over reverberant sound

$$\frac{direct\ sound}{reverberant\ sound} \qquad [2]$$

In the following graphs the direct sound SPL is the white curve (impulse response is windowed in the first 25ms, so SPL is correct from 40Hz and above), the red curve is the SPL considering the complete impulse response (so direct sound + reverberant sound), the green curve is the SPL applying a window from 20ms to 600ms (so reverberant sound reaching microphone after 20ms), etc (see detailed legend at the bottom right of each graph).

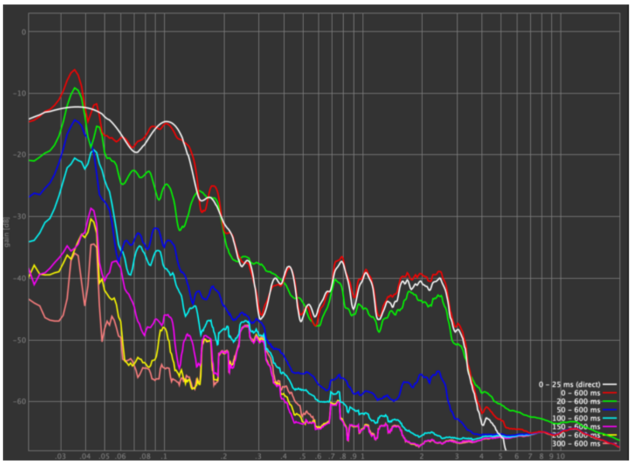


Fig7: Trunk subwoofer @driver seat

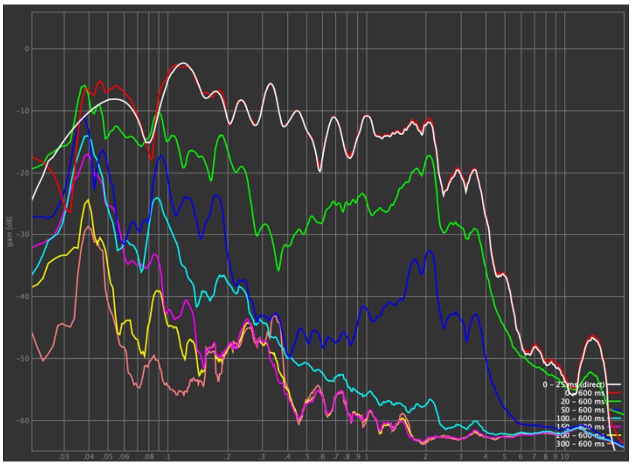


Fig 8: Left front woofer @driver seat

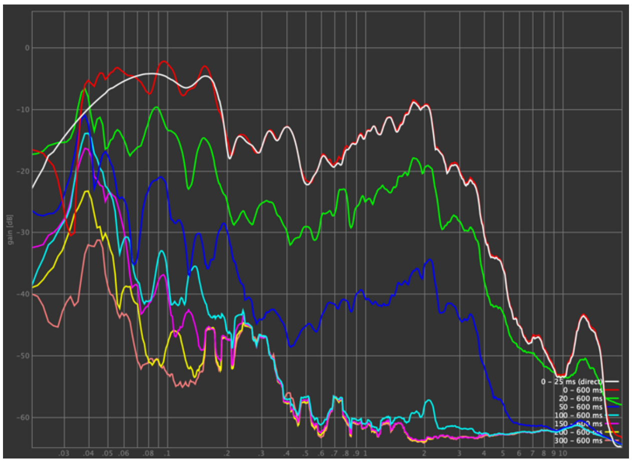


Fig 9: Right front woofer @diver seat

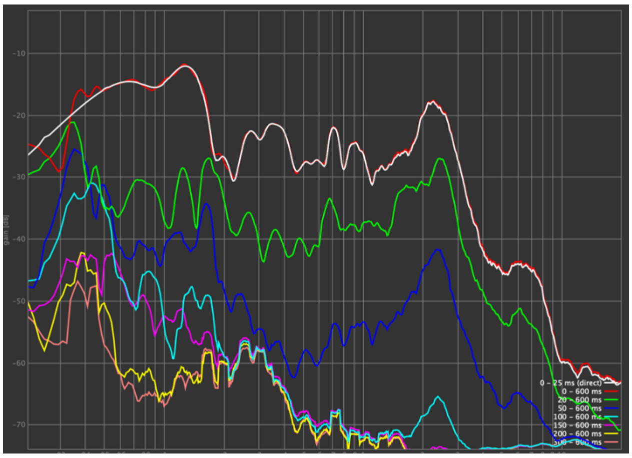


Fig 10: Central push-push @driver seat

These graphs show a clear benefit of the central push-push: the reverberant sound is about 15dB or more lower compared to the direct sound (fig 10) whereas it is about 5dB lower for trunk subwoofer or door woofers. It is also highlighting the central push-push is less exciting the room eigenfrequencies. This explains why the central push-push provides much cleaner, more accurate and tighter bass compared to other solutions. This situation is the same on the rear seats:

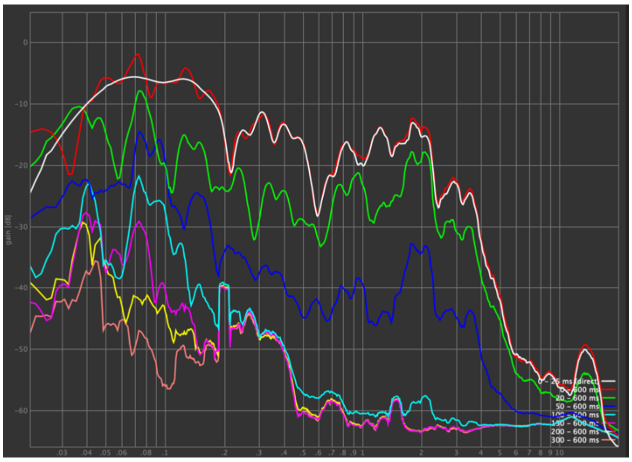


Fig 11: Left front woofer @rear right seat

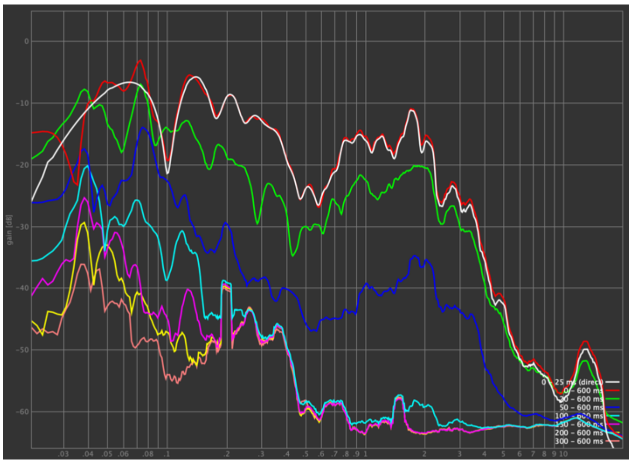


Fig 12: Right front woofer @rear right seat

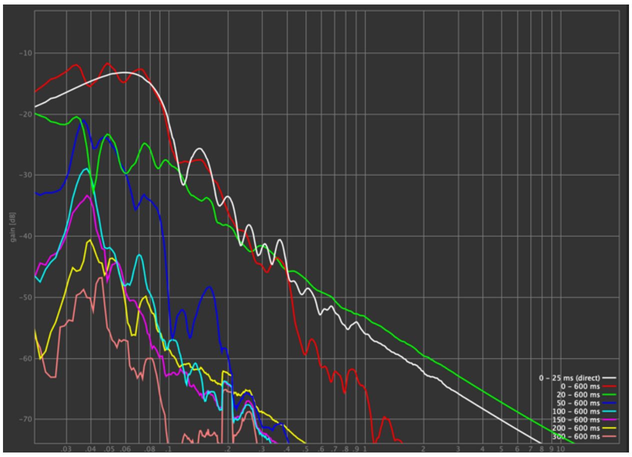


Fig 13: Central push-push @rear right seat

4. Optimizing the position of the central push-push

We have then analysed what would be the best position of this central subwoofer on the y0 axis. This analysis has been done by simulation using Comsol in a standard SUV car cabin considering only acoustic physics (no mechanical physics) with simple "generic" boundary conditions. Four subwoofer positions have been analysed with a 6 microphones array at each passenger seats (SPL shown is an average of these 6 microphones). Combination of two push-push boxes has also been analysed.

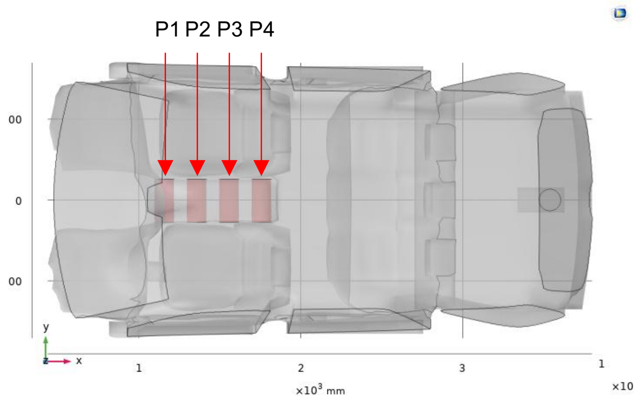


Fig 14: Presentation of the car cabin simulated, and the 4 positions simulated

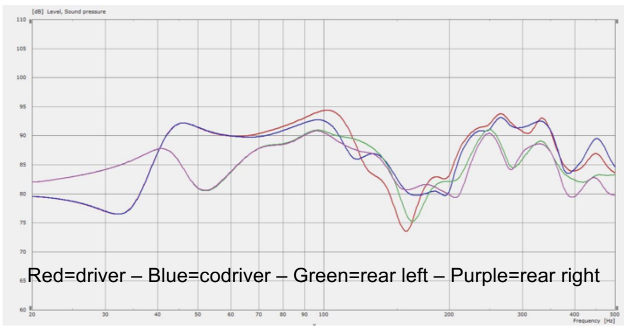


Fig 15: P1@all seats

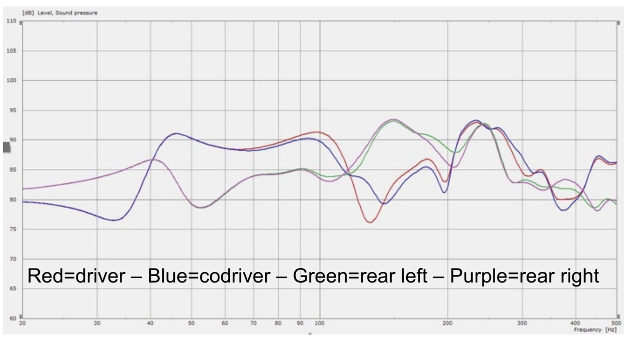


Fig 16: P2 @all seats

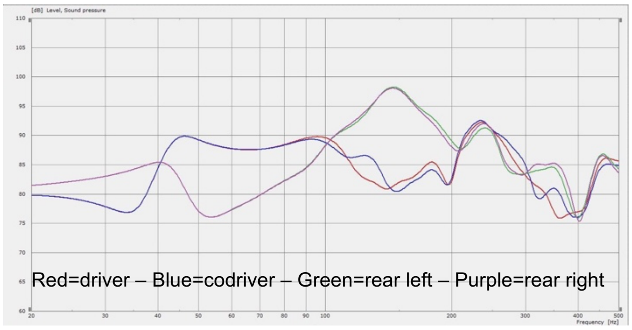


Fig 17: P3 @all seats

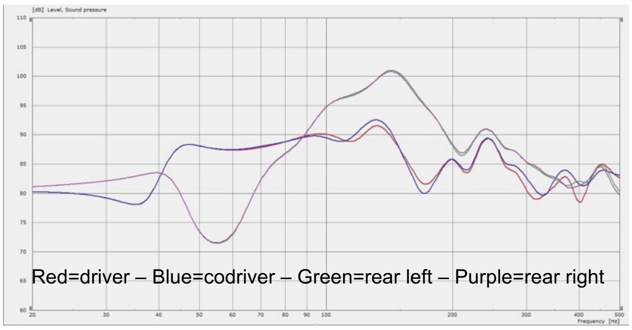


Fig 18: P4 @all seats

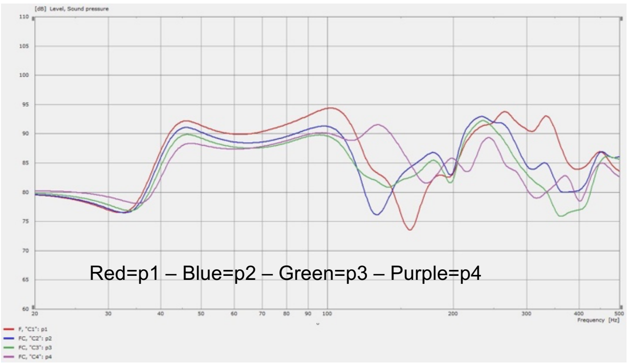


Fig 19: comparison of push-push position @driver

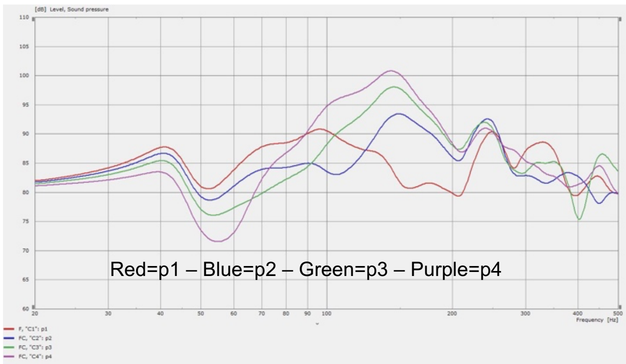


Fig 20: comparison of push-push position @rear right

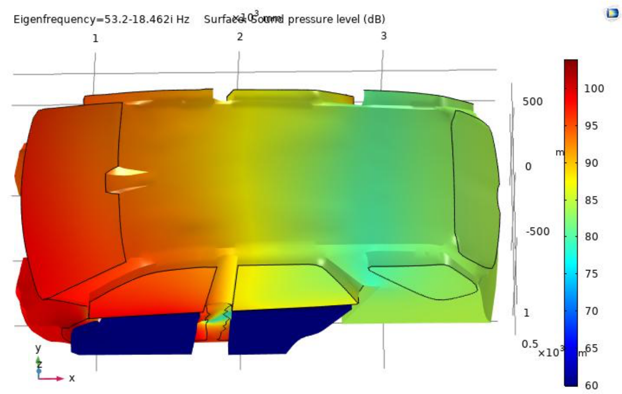


Fig 21: Room mode @ 53Hz

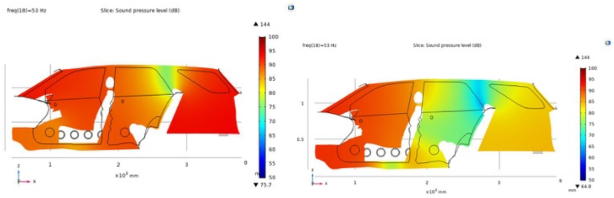


Fig 22: SPL @53Hz - left=P1 right=P4

Clearly the position offering the best repartition over the whole cabin as well as the smoothest frequency response with the less room mode excitation is P1, the most in the front of the cabin. On fig 20 we can see that position P4 is exciting the most the first longitudinal mode. These simulation results have been confirmed with experimentation.

5. Challenges of this new architecture

5.1. Loudspeaker design

As we have seen previously, the push-push subwoofer box needs to be as small as possible. Thus it requires to use small loudspeakers in a small closed volume.

SPL at low frequencies is dependent on the acoustic flow rate. By using small loudspeakers, we need them to have a long linear excursion. Particularly in order to reduce THD, a lot of attention should be put on the magnet system design in a way to achieve a very linear and symmetric BL(x) nonlinear curve.

Regarding the midrange/fullrange design, it is important to consider that they should be able to play correctly at max level from at least 150Hz. Indeed, the crossover point between the push-push subwoofer and the midranges/fullranges needs to be as low as possible in order to avoid having a soundstage that could be too low or localizing the push-push subwoofer. Therefore the midranges/fullranges design needs also to consider enough linear excursion at these frequencies.

5.2 Amplifier sizing

As the push-push speakers are the smallest possible and used in a small closed volume, the efficiency of the push-push subwoofer box is pretty low compared to conventional trunk subwoofer or door woofer.

Thus, in order to achieve the same SPL we need to apply to the push-push subwoofer a much higher power. The smallest are the speakers the higher power will be needed. The power requirement can be challenging for automotive amplifiers. A solution to solve this issue is to use dual coil loudspeakers and two amplifier channels per speakers.

6.Conclusion

We have presented a new sound system architecture that solves some issues of conventional architectures:

- Removes door woofer and thus simplifies the door design
- Avoid rattling problems

And also brings many advantages on different aspects:

- Compacity
- Simplicity
    - Less speaker references
    - “Easy to tune” architecture
- Scalability from standard to high-end
- Performance
    - No parasitical vibrations
    - Dry bass thanks to a better direct sound/reverberant sound ratio
    - No intermodulation distortion as bass and midrange are reproduced by different speakers
    - Optimum front/rear bass repartition
- Privacy (high level of privacy without door woofers)

7. Acknowledgement

We would like to thank the company Sonavox for giving us the opportunity to build prototypes of our concept and test it. They also provided us many loudspeakers for optimization purposes.
We also would like to thank Daniel Fournier who followed us and supported us in developing democars for Stellantis, which helped us evaluating the potential of this sound system architecture.

8. References

[1] Roy, A. T., Vigeant, M., Munjal, T., Carver, C., Jiradejvong, P., & Limb, C. J. (2015). “Reverberation negatively impacts musical sound quality for cochlear implant users”. *Cochlear Implants International*, *16*(sup3), S105–S113. Published: 12 Nov 2015