# Influence of equivalent impedance on acoustic response of flat panel speaker

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*Abstract*— **The main goal of this paper is to explore correlation between equivalent impedance and acoustic response in frequency domain of flat panel speakers based on DML technology. This correlation was examined considering three different ways of using flat panel speaker that are often encountered in practice: stand-alone panel, panel built into shallow plasterboard wall and panel built into large free-standing one-layer plasterboard wall with open back. Influence of different types of panel installation on resulting acoustic response also was examined. Measuring results are presented showing strong correlation between equivalent impedance and acoustic response. It was concluded that acoustical response of flat panel speakers can be predicted very precisely based on the frequency characteristics of the impedance, thus encouraging further research and development of more exact equivalent electro-mechanical impedance model of flat panel speaker.**

## 1 Introduction

Over the past few years we have witnessed the appearance of flat panel speakers based on bending (flexural) wave propagation, like Distributed-Mode Loudspeaker (DML) [1] and similar technologies. From interior designer's point of view probably the most interesting products based on this kind of technology are so-called "invisible in-wall" speakers, expression often used for flat panel speakers built directly into the walls made from light materials such as plasterboard, plywood etc.. In this paper we examine the sound reproduction quality of built-in flat panel speakers influenced by real-life conditions as well as the possibilities for predicting their final acoustic response based on the measurement results of their equivalent impedance.

## 2 Theoretical principles

Flat speaker panels based on flexural waves incorporate actuator (dynamic moving coil transducer) for exciting vibrations in the panel, thus causing complex standing wave patterns (modal patterns) over its entire surface at resonant (natural) frequencies. Frequency distribution of modes is mainly responsible for acoustic performance, as their superposition dictates radiation of sound waves. Modal behaviour mostly depends on the panel dimensions, mass and stiffness of material, among other properties. Without going into details, due to the limited length of this paper, we can conclude that panels with larger dimensions and bigger mass tend to have better low frequency response often followed with lower efficiency and vice-versa [2].

Typically, panel speakers are built into plasterboard walls by cutting an opening in the wall, inserting and tightly fixing the panel in the cutout. Panel is then skimmed with plaster (1-2mm) in order to get a flat surface, and covered with paint or wallpaper. A number of factors in this process affect final acoustic response of the installed panel loudspeaker, and several key factors can be distinguished [4, 5]:

1. Forming a fixed junction between the panel and the surrounding plasterboard wall allows transfer of vibrations to a larger surface attenuated by the mechanical impedance change in the junction.

2. Adding mass (plaster, paint...) to the front side of the panel speaker reduces modal activity, thus reducing overall efficiency (lower SPL) mostly in the mid-range of frequency response.

3. Cavity inside the wall forms an enclosure on the back of the panel adding suspended mass to it, thus changing mechanical properties of the panel, resulting in the frequency shift.

4. Reflected sound waves from the rear wall at the back of the panel affects vibration propagation, attenuating mode activity at some and amplifying at other frequencies, resulting in audible peaks and sound coloration.

Enclosure influence on cone membrane loudspeakers is described in studies of A. N. Thiele and R. H. Small, who present calculations with TS small signal parameters derived from impedance curve of the loudspeaker [6]. Nowadays, based mainly on their models and equations, many easy-to-use software tools have been developed for speaker enclosure design and for predicting acoustic response of speakers with satisfying accuracy.

The Distributed Mode Loudspeaker (DML) is an electro-acoustic transducer based on the radiation of modal bending wave shapes [1]. The final effect is that in the far-field such vibrating diaphragm produces an acoustic image that is the result of the superposition of the huge number of individual mechanical driving points. Since these driving points are small compared to the wave-length of the sound wave in the air, approximately true point of source radiation can be

achieved. Closer to the DML panel type of the sound source a complex radiation pattern can be observed.
The DML panel is driven at choosen points by specially designed electromechanical transducers known as exciters. These electromechanical transducers are usually an inertial drivers with an electro-dynamic motor. For an even frequency distribution of modes excitation points are chosen in such a way that as many modes as possible are excited.

The mechanics of such an exciter are similar to conventional loudspeaker drivers, except that the mass of the permanent magnet must be taken into account and that there is no diaphragm that is permanently attached to it. A single panel can be driven using multiple exciters. In all DML simulations it must be taken into account that the mechanical domain is strongly influenced by the way the panel is mounted in a frame (or a wall) and connected to the exciters. Therefore it is appropriate to use special elements for the analogy with electro-mechanic transducers and mechanic-to-acoustic transmission. [3]

The exciter drives the panel either by principles of inertia or bending. The motor of the exciter is usually an electrodynamic or a piezo driver. Within the magnet field the current in the voice coil is accelerated inducing a force F. The magnet has the mass Mmm and the voice coil has the mass Mms. The voice coil assembly is suspended by a compliance Cms. Losses are represented by a mechanical resistance Rms. The mechanical resistor Rms is omitted here and is thought to be in parallel with Cms. Figure 1 represent the equivalent impedance analogy circuit. The left part symbolises the electrical details of the motor including the impedance of the voice coil Zes. The circuit can be represented as a five-pole where the branch with Cms and Rms functions as a virtual or 'floating' common. The panel is connected to the voice coil branch Mms. If no additional forces are acting on the exciter the magnet-branch Mmm and the suspension branch Cms are grounded. [3]

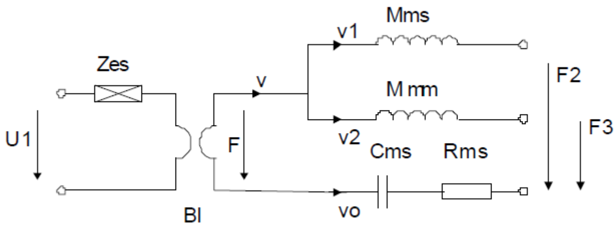


Fig 1: Electro-mechanical equivalent circuit of DML exciter

For the DML, on the other hand, equivalent electrical models were derived by N. J. Harris and M. O. J. Hawksford and they included equations that give a hint on frequency response and efficiency, but are, generally speaking, very approximate [1]. In our opinion, the complexity of modal activity calculations hinders the creation of a credible and simple enough model capable to analyze equivalent electrical behaviour of the exciter attached to a panel. Physics-based simulation softwares, like Comsol Multiphysics® can help in the mechanical analysis of this situation.

One of the aims of this paper was to find a correlation between impedance curve that can be easily measured and acoustic response of the flat panel speaker, with the focus on detection of resonant frequencies and their distribution in audible frequency range.

## 3 Measurement setup

### 3.1 AMG Sound Tube System panels

For the purpose of this paper, measurements where conducted on a flat panel loudspeaker manufactured by AMG company located in Belgrade, Serbia. Panel is made of layered honeycomb-like material, driven with two exciters, fixed in a rigid, partially closed metal frame. Dimensions of the panel are 44cm x 32cm x 0.5cm, with nominal impedance of 8Ω and power handling of 30Wrms. Panel loudspeaker is specially designed for in-wall mounting in plasterboard walls, as described in the previous section [7].

### 3.2 Panel placement and ambient characteristics

To examine the theory predictions in real-life conditions, measurements were conducted in three typical situations:

1. Non-built panel hanging 1.5m from the ceiling, with a minimum distance of 1.5m from any other object.
2. Panel built into a shallow plasterboard wall, dimensions 250cm x 250cm, 6cm away from rigid wall surface, with plaster covering approx. 2mm thick, and semi-dispersive paint for interior decoration.
3. Panel built into a large free-standing one-layer plasterboard wall with open back, dimensions 420cm x 320cm with plaster covering approx. 2mm thick, and plastic wallpaper covering the whole front surface

Measurements were performed at AMG's technical center in Belgrade where previously described panel loudspeaker and wall constructions are installed. AMG's technical center/experimental lab is located at the ground floor of a shopping mall, with floor surface of $15m^2$ and ceiling height of 3.2m. The room has average reverberation time of 0.3s in the mid frequency range, with other acoustic properties expected to be found in average living or similar kind of room.

### 3.3 Measurement devices and software

All measurements were performed at 1m distance from each panel centre, using dedicated software EASERA by AFMG for generating logarithmic sweep signal and measuring impulse response of the system. Signal was fed through linear power amplifier connected to panel terminals. On the receiving side of the measurement chain a calibrated Neutrik NTI Audio Mini SPL measurement microphone along with DigiDesign Mbox-2 sound card was used.

Impedance measurements were performed using a special device for speaker's impedance curve measurement, designed by one of the authors of this paper [8]. Device is based on a high precision impedance-to-digital signal converter incorporating a digital signal synthesis algorithm, A/D conveter and DSP for measurement. Panel speaker was excited with sinusoidal constant current of 7mApp in order to stay in small signal measurement boundaries even at high impedance values. Device measures complex impedance values in frequency range 20Hz – 30kHz, in 1.100 points with even octave distribution, and has a relative error of 1% for magnitude and 5% for phase, which is appropriate for the purposes of this measurement.

## 4 Measurement results

Impedance and acoustic measurements were performed in all three situations described above, and results are presented as combined graphs in highest available resolutions, with 1/12 octave averaging in acoustic and no-average in impedance curves, to get most detailed graphs as possible. Acoustic measurements in this case imply the generation of frequency response curves based on the FFT algorithm applied on the results of impulse response measurement conducted within dedicated EASERA software.

### 4.1 Non-built, stand-alone panel

For the stand-alone panel setup, measured results are shown with impedance curve in the upper and frequency response at the 1m distance in the lower part of Figure 2. Upper curve of the first graph represents the results of the phase measurements, while the lower curve shows the results of measuring the amplitude of the impedance. Second graph represent the results of acoustic measurement, namely the frequency response curve at 1m distance from the center of the panel.

Resonant frequencies of the exciter-panel system can be noticed as sharp peaks in both phase and magnitude impedance measurement results. Modal activity that results in increased SPL can be observed in acoustic measurement graph in form of peaks at resonant frequencies.

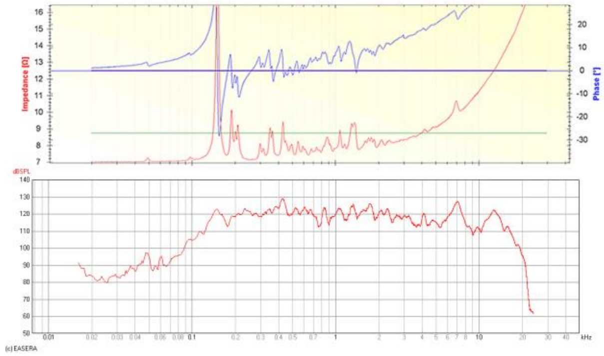

Fig. 2 Non-built, stand-alone flat panel speaker impedance (phase and magnitude) and frequency response at 1m distance

Flat panel loudspeaker's lowest resonance frequency is at 150Hz, and the highest one can be found at 7kHz. In acoustic response highest peak at approx. 12kHz is more likely influenced by harmonics rather than resonant frequency of the panel, as there is no impedance change at this frequency. In the lowest frequency range there are slight resonances occurring at frequencies just below 100Hz and 50Hz, but both do not result in a significant SPL due to panel dimensions and other properties.

### 4.2 Panel built into a shallow wall

Measured results for panel built into shallow plasterboard wall are shown with impedance curve (upper-phase, lower-magnitude) in the upper and frequency response in the lower part of Figure 3.

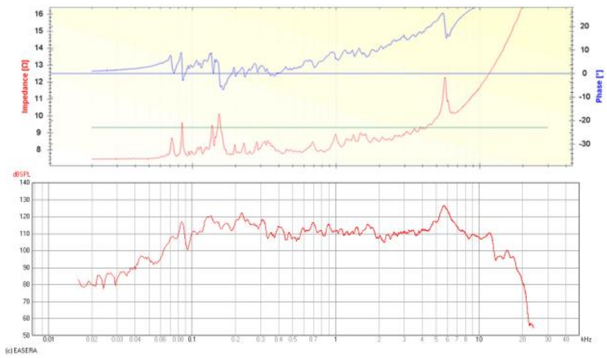

Fig. 3 Flat panel speaker built into shallow wall impedance (phase and magnitude) and frequency response at 1m distance

If we compare these with the previous stand-alone panel situation results, we can notice more, but not so pronounced, resonant peaks below 200 Hz. In the same time, the main resonant frequency in high frequencies region moved to the left, from 7 kHz (non-built panel) to 5.8 kHz (built-in panel). Plaster and paint covering add significant amount of mass to panel. This kind of increase in total mass of the panel results in overall decrease of panel vibration, lowering total amount of acoustic energy emitted in the mid-range frequency region.
On the other side, because of the rigid connection with the rest of the wall, bending waves do propagate to surrounding plasterboard surface to a certain degree.

This in a way can be considered as increase in overall dimensions of the panel, thus enabling the appearance of greater modal activity in the low frequency region. All those results in shifting resonances to lower frequencies have strong influence in final sound reproduction, in the sense of more pronounced low frequencies content in overall sound emitted from panel.

### 4.3 Panel built into a large wall

Measured results for panel built into a large free-standing one-layer plasterboard wall are shown with impedance curve in the upper and frequency response in the lower part of Figure 4.

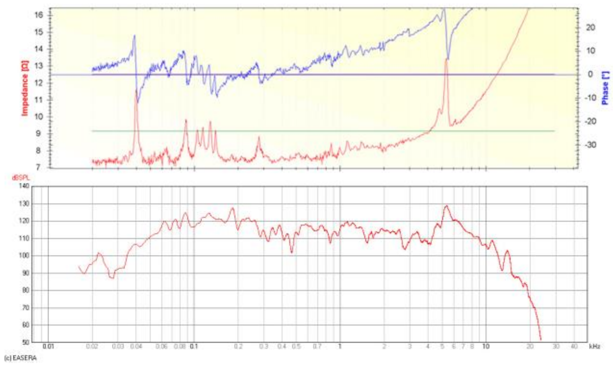

Fig. 4 Flat panel speaker built into large wall impedance (phase and magnitude) and frequency response at 1m distance

Similar to previous situation, resonant frequencies within lower frequency region moved to the left, with highly pronounced impedance peak at resonant frequency of 40Hz. Huge wall dimensions and the absence of suspended mass load on the back of the panel provide conditions for obtaining higher SPL even bellow 100Hz. Plastic wallpaper over the front surface attenuates mid-range frequencies more than paint in the previous case, as expected.

## 5 Conclusion

Based on measured results we can draw the following conclusions:

1. There is a clear correlation between measured impedance values and acoustic response of DML based panels in each and every analyzed situation, which can be easily observed as a precise match of resonant frequencies.

2. As a result, we can say that, depending on electrical impedance measurement of any DML based system, it is possible to predict the final frequency response.

3. Influence of real-life ambient conditions, like wall surface dimensions and depth, can significantly change frequency response of the panel speaker. It is then possible to get low frequency response from small panel loudspeakers built into huge walls. This potentialy eliminates the need for subwoofers in this kind of sound systems.

4. Measured results are consistent with the theory and have confirmed earlier work and measurements conducted by one of the authors of this paper [5].

Authors hope that this paper sheds new light on the idea of using simple electrical impedance measurements as an aid in designing flat panel loudspeaker systems. Such measurements can also be useful tool for the analysis of already installed sound systems, as well as for predicting acoustic response in real-life conditions.

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