NTNU – Trondheim
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DML in VIDEO-CONFERENCING APPLICATIONS

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Problem description

How will the DML speakers from the company e-Scape work with three or less exciters in a dipole set-up, in video-conference applications? How is speech-intelligibility, naturalness of the sound and do one get a better closeness to the one speaking to, compared to ordinary monopole video-conferencing speakers mounted on wall? When watching the video-screen, is it a problem that the sound is not coming from the screen when listening to the DML?

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Sammendrag

Dagens lyd- og høyttaleroppsett i video-konferanserom innehar ikke alltid høy lydkvalitet. I de fleste av oppsettene er PC-høyttalere montert på veggen, og en mikrofon på bordet. Ved denne plasseringen blir det ofte eksitert sterke rom-moder. Når du snakker med noen som har begrenset lydoppsett, kan tale-forståelsen være virkelig ille.

Denne masteroppgaven presenterer en løsning som kan forbedre høyttaler-oppsettet i video-konferanserom ved å montere en DML høyttaler (Distributed Mode Loudspeaker) over- og parallelt med konferanse bordet. DML høyttaleren er et plexiglass panel hvor det er montert en eller flere drivere, som på engelsk er definert som "exciters". DML høyttaleren sender ut lyd på begge sider i motsatt fase, som en dipol. Dipoleffekten kan videre minimere utstrålingen av lyd til tak og kontorbordet. Høyttaleren er designet og modifisert av en høyttaler opprinnelig produsert av høyttalerselskapet e-Scape.

Ideen om å montere DML høyttaler over bordet er at publikum vil få en nærhet til lydkilden, og rom-effekter kan være svært lave i forhold til det direkte lydsignalet. Dette bør gi en mye bedre tale-forståelighet av det som oppfattes som lydsignalet i forhold til eksisterende løsninger.

Etter å ha målt ulike kombinasjoner av to og tre drivere i et ekkofritt rom, viser resultatene i denne masteroppgaven at den polare frekvensresponsen av èn driver har en mye bedre frekvensrespons enn de andre kombinasjonene. På bakgrunn av dette ble det foretatt en undersøkelse hvor 19 deltakere skulle teste ut forskjeller mellom DML høyttaleren og PC- høyttalere. De subjektive testene viser at flertallet av deltakerne foretrekker DML høyttaleren fremfor PC-høyttalerene på alle områder. Deltagerene mener DML høyttaleren gir en mer naturlig lyd og mer nærhet til den som snakker, samt en bedre tale-forståelighet.

Videre viser resultatene fra målingene i ekkofritt rom, og fra de subjektive testene en lav SPL (Sound Pressure Level) i lav-frekvens området. Under 100 Hz området av DML høyttaleren er SPL redusert ganske mye. Fra dette frekvensen området ser vi også noen dipol effekter fra resultatene. Dette kan gi gode kvaliteter som mindre stråling til taket og kontorbordet.

Abstract

Today's audio in video-conference rooms do not in general have high quality audio standards. Most of the set-ups are PC-Speakers mounted on the wall, with a microphone on the table. With this, strong room modes are often excited from the speakers. When speaking to someone which also have bad equipment, the speech-intelligibility can be really bad. One solution presented with this Master thesis is to improve the loudspeaker set-up by mounting a DML(Distributed Mode Loudspeaker) above and parallel to the conference table. The DML will then radiate sound on both sides of the table equally in opposite phase, like a dipole. This will also minimize sound-radiation to the ceiling and the office-table. The DML is designed and modified from a loudspeaker originally deigned by the loudspeaker-company e-Scape.

The Plexiglas panel, made out of an Acrylic material, has exciters mounted on the panel. After testing different combinations of two and three exciters in an anechoic chamber, the polar frequency response of the DML with only one exciter had a much better response than the other combinations.

The idea of mounting the DML over the table is that the audience will get closer to the sound source, and room-effects will be very small compared to the direct signal. This should give a much better speech-intelligibility of the perceived sound signal compared to existing solutions. Subjective tests show that the majority of the participants preferred the DML rather than the PC-Speaker in all areas; a more natural sound, more closeness to the one speaking and better speech-intelligibility.

One problem, which is seen on the measurements and feedback from the participants on the subjective test, is a low SPL(Sound Pressure Level) in the low frequency area. Under 100Hz the magnitude of the DML is reduced, compared to the response of ordinary monopole speakers. From this frequency area one can also see some dipole effects from the results, which gives us good qualities such as less radiation to the ceiling and the office table.

Acknowledgment

I would like to dedicate this page to my appreciation of all the support I have been given throughout this Master Thesis.

I want to give a big thanks to the support from all the test-subjects taking their time to make the test a reality.

Thanks to my main supervisor Odd K. Pettersen from Sintef for the idea of using the DML in video-conferencing applications.

The support from the C.E.O from the company e-Scape, Runar Kjølle Nilsskog and his companion Robin Støckert has been more than expected, and appreciated very much.

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1.1 Background

Loudspeakers in video-conference rooms today has big variation in quality. Cheap set-ups will have very random quality, but rarely good. Well designed and equipped conference rooms will have good sound quality and good solutions to the set-up. Such a set-up is very expensive, especially for small companies which can not afford such an investment. A normal set-up is to place two cheap pc-speakers up on the wall at each side of the screen, which can be bad if some people are sitting closer to the speakers than others. Microphones are usually placed on the table, and often just one. This makes it harder to hear people which are sitting far away, compared to the people which are sitting next to. Some people might find their set-up so bad, that they choose not to use video conference because the sound quality is very bad. Video conference is a very useful tool for many people, and improvements are needed.

1.2 Current problem

Most conference rooms are built to look good, not for good acoustic conditions. When placing speakers on the wall, they can give a "boomy" sound at the low-frequencies, especially if the speakers are placed near the roof corners, since most room modes will then be excited. The distance from the loudspeakers to the audience can vary a lot, the volume has to be set to the people which are sitting far away, then the people near the speakers might get exposed to louder sound pressure level than comfortably suited. When doing a video conference in a meeting with more than one person at each location or multiple locations, it can be very hard to have a efficient conversation when many people are talking at once. The body language is not present in the same way as ordinary meeting, and one have to rely on good audio quality to get a good speech-intelligibility. When bad quality speakers are placed in a corner, in a conference room with long reverberation time, simple communication can be very hard. When all these factors are combined, the speech quality will be very poor, and one would have to concentrate very hard to hear what people are saying. When video conferences are this bad, the work environment is not proper for efficient or comfortable work to be done.

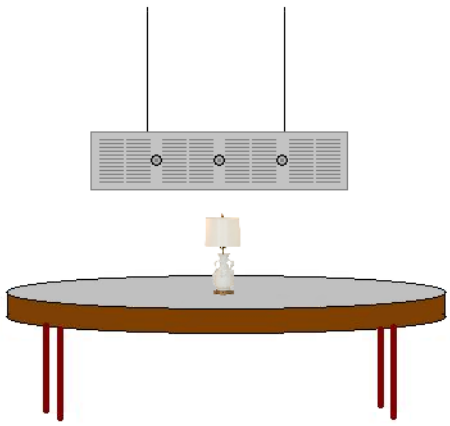

Figure 1: An illustration of the DML over an office table

1.3 Proposed solution

The solution this paper is looking at, is a version of a loudspeaker from the company e-Scape. It is a Plexi-glas panel made out of Acryl with small slots, called Distributed Mode Loudspeaker (DML). Up to three transducers will be mounted on the panel, and there will be measurements to see how many are need to get the best symmetric polar frequency response. The idea with the DML is to place it above and parallel to the conference table, so that listeners are more close to the sound source. By doing so, one also avoid negative effects on the sound affected by the room. This means the direct sound field will be dominant compared to the reverberant sound field. The challenge by hanging a DML above a table is to design it so it will not dominate visual or block vision. The speaker will radiate sound to both sides like a dipole, such that listeners on both side of the table will get the same sound quality. The DML is known to have a good polar frequency response when the dimensions are 60cm times 60cm with one transducer [1], this version will be designed to 120cm times 30cm to fit better over a conference table, which might give a different result. Even though it might not be a perfectly dipole at all frequencies, which gives a figure of eight directivity pattern, it should still have some of the same characteristics as a dipole. The limitations are that there are no enclosure, so the lack of low-frequency might occur as a problem. Since the DML in this case is mainly radiating speech, the frequency spectrum from 80Hz to 8000Hz is mainly for speech, and low frequency under 80Hz will not be important. The sound pressure level might also be a problem if the material is too heavy and the shape of the DML does not give good acoustical properties to give efficient enough sound pressure level. The DML should ideally behave like a line source at all frequencies, and measurements will be done by using 1-3 transducers to find the best symmetric polar response.

Theory to understand the results is covered in chapter 2. The approach to the design of the DML is found in chapter 3. Chapter 4 shows the result of the DML measurements in a anechoic chamber and a subjective test. These results will be discussed in chapter 5, and the conclusion can be found in chapter 6.

2 Theory

This chapter will give an insight to the most important theory required to understand the proposed loudspeaker design. The different subjects are well documented in [5] and [2].

2.1 History

From the 1920's the best loudspeaker was conceived to operate like an ideal piston [5]. The loudspeakers at this time were driven by a moving armature, or later on a moving coil. The vision was to create a transducer that could control the sound radiated by a "pistonic" motion as good as possible.

To get an even frequency response from the diaphragm, which works as a moving mass, there are two requirements. The first requirement is that the diaphragm has to be small enough to approximate a point source, with constant acceleration that gives a flat frequency response. The second requirement is that the whole diaphragm moves at the same acceleration as an ideal piston.

A problem with this construction of a loudspeaker is that the radiator size is to small compared to the wavelength and effect being reproduced, and the solution to this is two or more diaphragm to cover the whole audible frequency range. This also introduces crossover problems, which is an art to master.

The fact that the diaphragm produces the same amount of energy out of both sides, since it is an open-baffle construction, the back side will be 180° out of phase compared to the front radiated sound. This has some good audiophile qualities, but it has a low SPL(Sound Pressure Level) in the low frequency range and falls 6dB per octave on-axis after cut-off [3]. Mounting the transducer in a cabinet and make it work like a mono-pole is difficult, since there is high energy output from the back of the diaphragm. This acoustic energy is damped inside the cabinet, but the big problem is to ideally avoid cabinet modes, standing waves and diffraction [5].

2.2 Distributed Mode Loudspeaker (DML)

The Distributed Mode Loudspeaker is different from traditional moving coil loudspeakers. In it's acoustical and mechanical properties it radiates acoustically completely different, by the use of bending waves as a source of acoustic radiation. It is defined as a new class of loudspeakers because of its difference to other loudspeakers mechanics. The typical properties of a DML is that it radiates due to uniform distributed, free vibration in a stiff and light panel. Since bending waves are dispersive, meaning the wave velocity is a function of frequency, a good approximation is to consider the panel as a randomly vibrating area. The radiation intensity from such an area depend on the square of the mean velocity, as it has to be constant. To achieve a constant velocity with a constant force, the mechanical impedance must be resistive. The expressions for bending waves velocity and mechanical impedance are displayed below [5], [4].

$$v(\omega) = \sqrt{\omega\sqrt{\frac{B}{\mu}}} \tag{1}$$

$$Zm = 8\sqrt{B\mu} \tag{2}$$

where;

B = bending rigidity of panel, Nm

μ = mass per unit area of panel,kg/m^2

Zm = mechanical impedance of panel, kg/s

ω = angular frequency, rad/s

2.3 Mechanical model

Since the panel has low mechanical loss, all the energy supplied to the panel is assumed to be dissipated by acoustic radiation. With this measurements confirm that the radiated pressure is proportional to the mean velocity in the panel. To calculate the acoustic power, the only calculation needed is the mechanical power delivered to the panel. This means that the sound pressure can be found from the mean panel velocity.

The DML is a resistance-controlled device and the basic mechanical arrangement is shown in Figure 2.

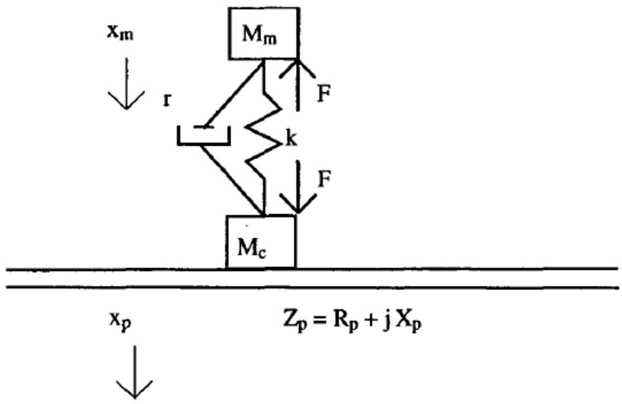

Figure 2: The Basic Mechanical Arrangement

2.4 Equivalent Circuit

The mechanical model can be transformed into an equivalent electrical impedance circuit by a method proposed by Bauer [6]. This method uses voltage-force-pressure analogy.

This project will not go in detail on the exciters electrical or mechanical analogy, but in figure 3 a "complete electro-mechanical schematic for a DML panel and exciter" can be further studied in [5]. A shot overview of the electro-mechanical schematic will be given below. The specifications of the exciter can be found in A.

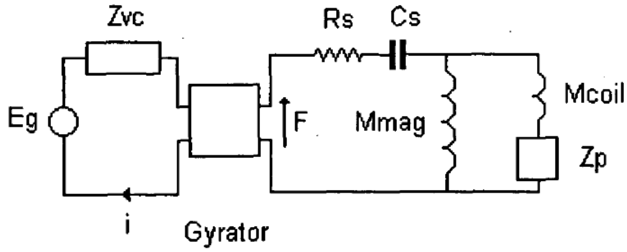

Figure 3: Complete Electro-mechanical Schematic for a DML Panel and Exciter [5]

From Figure 3 the velocity in the panels low frequencies are defined by the values of Cs and Mmag, acting as a high-pass filter. These values are chosen to match the panels mechanical impedance Zp. At high frequencies the velocity depends on the coils mass, Mcoil, and the value of the panel impedance Zp which can be seen as a flat response in Figure 4. The coil mass and coil inductance determines the high frequency limit.

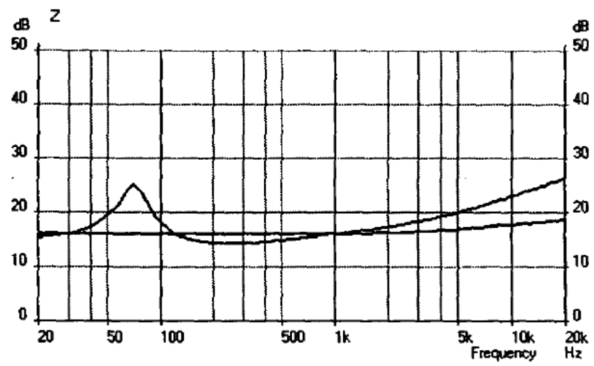

Figure 4: Terminal Impedance, Traditional speaker versus DML [5]

The impedance and the traditional moving mass loudspeaker is reactive and gives a classical low frequency electrical resonance, Figure 4. A DML panel is resistive and this is reflected in a flat terminal impedance curve.

When changes are made to the BL factor of the magnet/voice-coil in traditional loudspeakers, the whole low frequency performance is affected. In DML panel the change in the BL factor just affect the broadband output level. This comparison can be studied in Figure 5, to make the comparison fair, pay attention to the difference in the magnitude level on the two speakers.

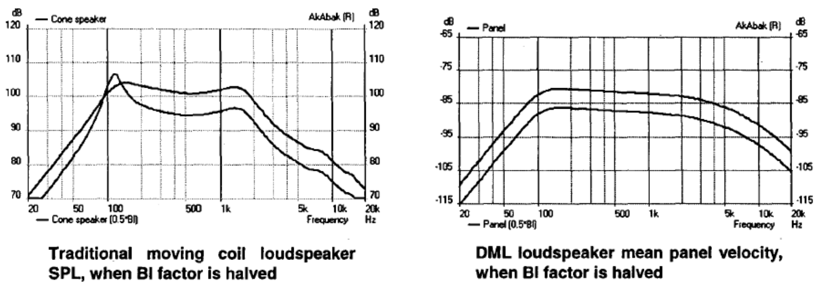

Figure 5: Reduction the in BL Factor, Traditional Speaker versus DML [5]

2.5 DML Directivity

Traditional loudspeakers have a narrowing directivity pattern as the frequency increases, and need normally two drive units to cover the audible band. For DML panels the directivity is independent of frequency. This makes the polar directivity stable up in high frequency.

The main reason to this is because of the diffuse nature of a DML panel, where there is a region close to the panel which the pressure remains constant. In rooms DML panels can use the rear radiation to support the front pressure region in such a way as to increase the region where the pressure remains constant. The DML panel has diffuse radiation and works good with diffuse reflections. With these two features combined a DML speaker excites far fewer room modes that a traditional loudspeakers [5].

2.6 DML Bandwidth

The bandwidth of the DML can be calculated from equations 3 and 4 which only depend on the ratio of magnet mass to coil mass. The panel properties affect the sensitivity and frequency limits only threw the mechanical impedance. It is possible to design a single DML to be substantially flat in pressure and power response over a very wide bandwidth without any electrical filters. This is something which is impossible to achieve with conventional loudspeaker technology [4].

$$f_{max} = \frac{R_\rho}{2\pi M_c} \tag{3}$$

$$f_{min} = \frac{R_\rho}{2\pi M_m} \tag{4}$$

A DML loudspeaker should work good as broadband acoustic radiator. It has many useful features [5]:

- It has a relative wide bandwidth from just a single radiator
- Diffuse sound-radiation is spatial
- Directivity and polar-pattern are frequency independent
- It requires not enclosure
- Back radiation is out of phase
- It has normally less than 6 dB/octave power loss
- Improved room interaction and no sweet spots
- A simple resistive load for the amplifier

2.7 Dipole Directivity

This chapter will give a basic understanding of a Dipole Directivity. This theory is well documented in [2] and [13].

The properties of an ideal dipole is that it radiates sound from both front and back with a phase difference of 180° . At 90° there should be complete silence as the area is completely out of phase. From a practical approach this is hard to construct as the acoustic centre normally variate from a sound source. The dipole directivity is shown in Figure 6 where the D is the distance in acoustic centre from the front to the back of the dipole sound source, λ is the wavelength. The DML is not a ideal dipole, but in some frequency areas it can get a dipole directivity and get the some of the same properties as a dipole. When a dipole radiates sound in a room, it will then limit the early reflections to the office table and roof.

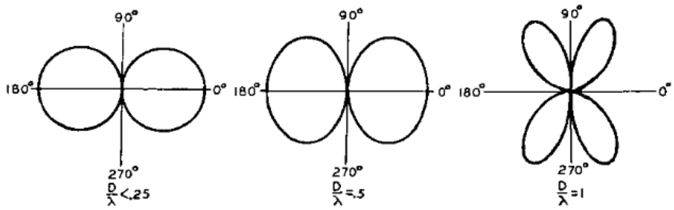

Figure 6: Directive pattern of a dipole speakers, from [8]

When the DML is mounted over the office table it will work as a velocity source, and the PC-Speakers which are a normal monopole, will work as a pressure source. This means that the DML should have better auditory localization than the PC-Speakers and excite less room modes if placed in a pressure anti node [3]. The DML is constructed as a line source and will get a directivity due to the superposition principle.

2.7.1 Diffuse Field of the DML

The position of the DML makes the diffuse sound field lower since the SPL is lower compared to the SPL of the PC-Speakers [13]. The diffuse sound field is a result of the reverberation time in the room. The diffuse field starts when the energy of the direct SPL is equal to the diffuse SPL. In [9] this distance is given by:

$$r_d = \frac{1}{4}\sqrt{\frac{A}{\pi}} \tag{5}$$

where A is the total sound absorption in a room.

2.7.2 Near field and Far field

Most of audience will listen to the DML in the near field, since they are positioned so close to the DML. The definition of where the near-field and the far-field meet, the transition point, is given by [10] and [3]; "The distance between an observation point and the center point of the line source is within a quarter of a wavelength compared to the distance from the same observation point, to the endpoint of the line source". The far filed is uniform, and the near field is discrete in most cases. If the DML has a ideal uniform response, there should be no theoretical difference of the near field and the far field, considering an infinite space. This will not be the case since the difference in acoustic center for each frequencies will vary as the DML is not a ideal point source. The transition point is calculated from:

$$r = \frac{l^2 f}{700} \tag{6}$$

where r[m] is the distance to the transition point , l[m] is the length of the source and f[Hz] is the frequency which is evaluated. From the equation 6 one see that the transition point is frequency dependent, this makes the near field small for low frequencies and large for high frequencies [12].

2.8 Subjective Testing

To confirm the measurements, a subjective test is required. This section will give a overview of testing conditions and recommendations from the ITU-R BS.1116-1 and ITU-R BS.1284, Radio communication, [7] and [8].

2.8.1 Recommendation ITU-R BS.1116-1 and ITU-R BS.1284

This recommendation states that conditions of listening tests which are tightly controlled on technical and behavioural sides, experience shows that 20 subjects tested should give sufficient data to get appropriate conclusions from the test.

Other recommendations suggests a lower number of subjects, depending on the test.

The recommendation suggests long- and medium-term aural memory is unreliable, and that the test should only rely on short term memory. Since the test is a comparison between PC- speakers and the DML, the PC- speakers will play first, then the DML. After this listening test the subject will answer only two questions, then the whole procedure will restart until the test is done. The time between testing each speaker should also be short.

The test scheme is based on the recommendations in [8]. The comparison scheme as seen in Figure 7.

	Comparison
2	Better
1	Slightly better
0	The same
–1	Slightly worse
–2	Worse

Figure 7: Recommendations of a Comparison Test [8]

It is recommended that no more than 10 to 15 trials per session, else the subjects fatigue may become a factor and interfere with the validity of judgements. If this becomes a problem, rest periods should be scheduled, and they should be longer than the session length. For two-channel stereophonic reproduction as room size of 20-60 m^2 is recommended. It should be bigger the more listeners are tested at the same time. The shape of the room should be symmetrical, relative to the vertical plane and the floor area should be a rectangle or a trapezium. The reverberation time in the room should be measured over the frequency range of 200Hz to 4kHz with values:

$$T_m = 0.25 \frac{V}{V_0} \frac{1}{3} \tag{7}$$

where

T_m = Reverberation time [s]

V = Volume of the room [m^3]

V_0 = Reference volume of 100m^3

Reverberation times at low frequencies can be difficult as there are usually a low Signal To Noise Ratio(SNR), due to ventilation noise and such. The recommendation suggests that "Early reflections caused by the boundary surfaces of the listening room, which reach the listening area during a time interval up to 15 ms after the direct sound, should be attenuated in the range 1-8 kHz by at least 10 dB relative to the direct sound" [7].

Even this is a good suggestion in a normal set-up, but this will not be considered in this test, as the reflections from the office table is a important factor of the experiment.

3 Design and Measurements

In this chapter the design process is described, and how the loudspeaker was measured in a anechoic chamber. Wiring of the speaker is also presented.

3.1 The approach construction a DML

The proposed solution of the design of the DML is a 120cm x 60cm x 0.4cm acrylic panel from DeAmp. The panel needs to be cut in half to better fit in a conference room to 120cm x 30cm x 0.4cm. It will then be mounted over and parallel to the conference table. With this open baffle solution, the idea is to get a line source with a uniform polar frequency response. The sound should radiate equal on both sides of the DML so that the participants on both sides of the table get the same sound signal from the speaker.

There will be tested and measured a combination of one to three exciters on the panel. The idea to use more than one exciter is to get a higher sound pressure level, this might not be the best combination, and this have to be measured. It is possible to get a single exciter with higher efficiency, which also can be a solution.

The properties that will be considered a good solution of the different combinations of exciters is; a good uniform polar frequency response, dipole characteristics and line source characteristics. The properties that will be negative are big frequency dips, uneven polar frequency response, out-phasing sound waves, out-phasing mechanical waves, cam-filter effects and other effects that will influence the listening experience.

The DML is not expected to be a ideal dipole since the radiation from the panel near the exciters will not be completely in phase with the radiation at the end of the panel, which is further away from the exciters. Still, if some frequencies are just radiated from a certain point, there might be dipole effects. These effects are very useful since it will make the speaker more directive, and dipole speakers have very good abilities in a room; if you listen at one end of a dipole speaker, the radiation on the other end will have such a long travel distance after hitting the building wall, compared to the direct sound. The human brain can actually hear it as a reflection, and not distortion in the direct sound signal. This effect will add depth and spaciousness to the sound image [2]. This ability is proven on a good dipole speaker, but as long as this DML does not have a very strong radiation at 90° , it will still have benefits from these properties.

As mentioned previously, the direct sound field will dominate because of the close distance between the DML and the audience. This makes the speaker very good for rooms with hard walls, where room modes and long reverberation time is considered a big problem. Another good quality is that if it works good as a line source, the radiation to the end walls will then be limited and the diffuse field will be reduced. Compared to regular PC-speakers, which do not have any any of these properties, the DML will theoretically better suited for a video conference [10].

The panel from DeAmp have micro laser-cut slots as seen in Appendix D. The micro slots are 0.2mm each, and the material is Acryl. These slots gives the panel absorptive properties when used with a back-box, but also significantly gain in the low frequency output [1]. The dimensions of the panel is as said earlier 120cm long, this limit is set because the company producing this panel only had this dimension in storage at this moment. Longer panels would also be possible for longer conference tables, but the bigger the panels gets, the higher mechanical impedance it will get, and more power from the exciter and the amplifier is required. If the case would be that the conference table is very long, it is possible to use additional DML speakers to cover the listening experience of the audience. The geometry of the DML will give a special sound signature, as it will not give the same polar frequency response, as the rectangle version which already has bin tested with a back-box, see [11].

The exciter used comes from Elac and is called Autotune Exciter 3720 KST 37mm. They are quite expensive and have a pretty flat frequency response, but there are exciters with a longer driving range. This ability will make a gain in the low frequency SPL, but it might add distortion to the sound signal in other frequency bands. For more specific details about the exciter see Appendix A.

3.1.1 Wiring of DML

The wiring of the panel speaker was made in series with all the combination of the 3 exciters, this implies that with 1 exciter has the impedance 8Ω, 2 exciters 16Ω and 3 exciters 24Ω, see Figure 8. To get a comparison how the different efficiency between the three different set-ups, each set-up is measured with a voltmeter with a continuous 1000Hz tone playing. The sound card output volume is then adjusted so that each set-up will get approximately the same output effect by this formula, $W = \frac{V^2}{R}$. Doing this attempt on calibrating each set-up, the sound card on the measuring-PC have big steps in the output gain. One will then not get a scientific comparison in output-effect. When comparing the different set-ups, the output sound power level should be seen as an approximation.

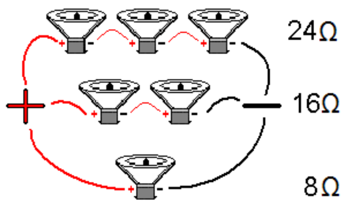

Figure 8: Wiring combinations of the Exciters

3.2 Measuring the loudspeaker

The loudspeaker is measured at a anechoic chamber at NTNU. The equipment that is used is a Norsonic omni-directional microphone, BSWA 216, a power amplifier "Quad 50E", a PC with "Lynx Two C" sound card and WinMLS 2004 measuring software. The amplifier was measured and had only a variation of 0.5dB for frequencies over 200Hz, and is considered ideally flat. See Appendix B and C for specifications.

When the loudspeaker was measured it was rotating around its own axis, both the horizontal measurement and the vertical. This means that at 90° the far end of the speaker is 60cm closer to the microphone than the 0 degree measurement. Still the other end of the speaker is 60cm further away. Since a line source in the far field can be seen as a point source, the change in distance should not matter. The use of the speaker is in the near field, but the audience are not going to sit on an greater angle than 45° , if so, then another panel speaker should be installed. This means the change in distance measuring the speaker leaves a room for error, mainly in magnitude. The DML was measured from 2.5m from the microphone.

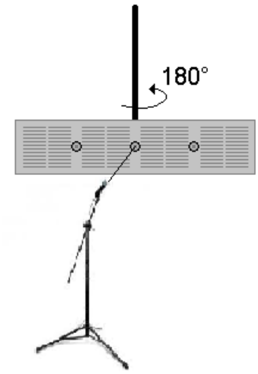

Figure 9: Measuring the Horizontal plane with a resolution of 10° , as rotating the DML 180° around its own axis

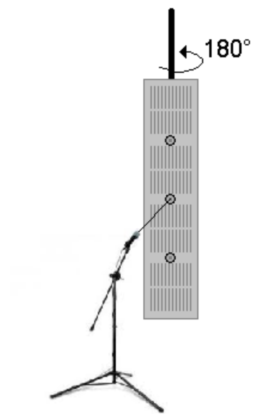

Figure 10: Measuring the Vertical plane with a resolution of 10° , as rotating the DML 180° around its own axis

4 Results

This chapter will present the results from the physical measurements of the DML in an anechoic chamber. The horizontal plane is the plane parallel to the ground, see Figure 9. The vertical plane is the plane perpendicular to the ground, see Figure 10. The measuring results have a 1°- 3° margin of error due to the equipment not being accurate.

Figure 11: Live picture of the front side of the DML in a anechoic chamber

4.1 Measurements

In this section the results from the polar frequency measurements are presented. To clarify the measurements; 0° is directly in front of the DML, 180° is directly behind the DML.

4.2 Polar Plots

The polar plots are meant to get a impression of the polar frequency response of some chosen frequencies. One can compare the magnitude differences and symmetry of the polar frequency response for the different combinations of exciters.

4.2.1 Horizontal Plane

The horizontal plane are a important measurements in this application, since the DML is mounted above a office table, see Figure 1. If the polar frequency response is not satisfying, the audience will experience audible differences with small change in head positions.

With one exciter the polar response is relatively symmetric up to 1000Hz, up in frequency there are some unevenness. Figure 12 shows a small dipole directivity up to 400Hz.

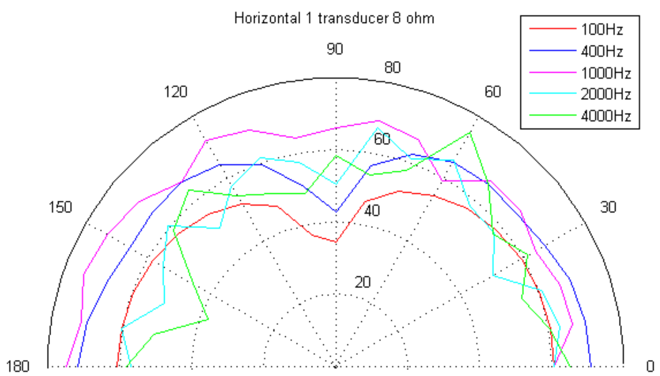

Figure 12: Polar response, measured Horizontal with one Exciter 8Ω

The set-up with two exciters have a very good dipole characteristics, but only at 100Hz. Figure 13 shows signs of interference or out-phasing on several frequencies. The magnitude of the different frequencies are more spread out than with one exciter.

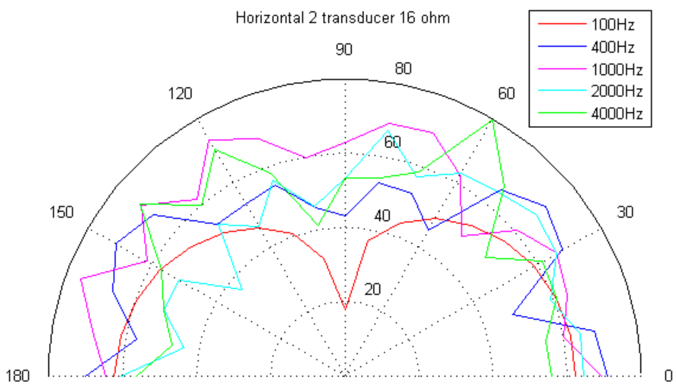

Figure 13: Polar response, measured Horizontal with Two Exciters 16Ω

The dipole effect works pretty good with three exciters. Figure 14 shows that 100 Hz behaves like a perfect dipole at 90° . At higher frequencies there are many dips in the magnitude and gives a unsymmetrical polar frequency response.

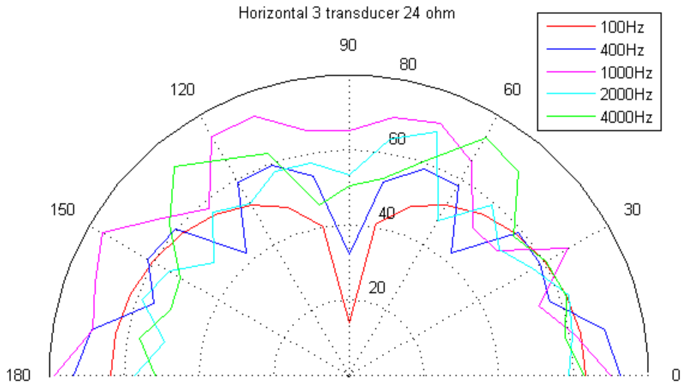

Figure 14: Polar Response, measured Horizontal with Three Exciters 24Ω

4.2.2 Vertical Plane

When measuring a line source from the vertical plane, the dipole directivity should be stronger when increasing the amount of transducers mounted on the panel, if mechanical theory is considered. This should mean that the panel should play more in-phase the more exciters, and closer to a perfect dipole. Measurement setup is illustrated in Figure 10

Figure 15 shows dipole effects for 100Hz and 400Hz. The magnitude is pretty symmetric at each frequency, but has some SPL differences. At 2000Hz there is a remarkable dip in magnitude at 150° .

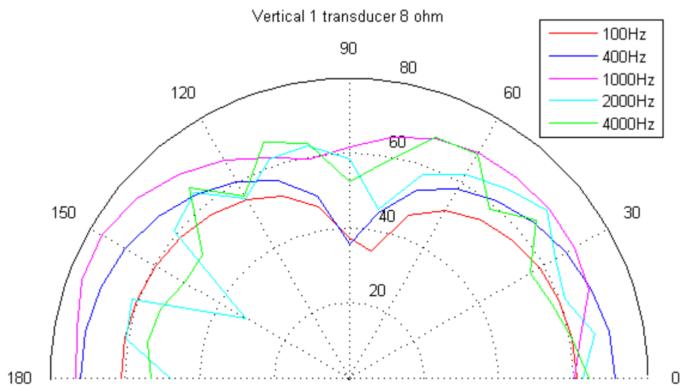

Figure 15: Polar Response, measured Vertical with one Exciter 8Ω

The setup with two exciters has a noticeable dipole directivity at 100Hz and 400Hz. The 1000Hz is some-what symmetric, still, one can see a lot of uneveness up in frequency. See Figure 16.

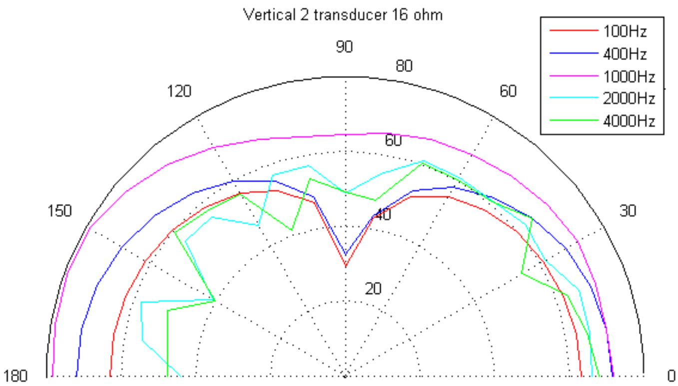

Figure 16: Polar Response, measured Vertical with Two Exciters 16Ω

In this set-up, the theory about the more exciters the better dipole directivity seem to fail. This might be caused by too much interference from the three exciters. The midrange has a pretty symmetric polar response, see Figure 17. As for the other set-ups, the highest frequencies are uneven and non-symmetric.

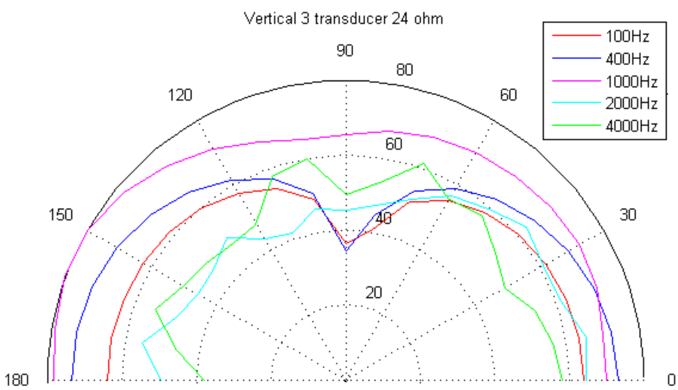

Figure 17: Polar Response, measured Vertical with Three Exciters 24Ω

4.3 3D Plots: Horizontal Plane

This section is will show 3D plots of the frequency response as a function of angle, from 0° to 180° . The purpose is to give a complete result of the polar frequency response. This can be hard as the 3D plot only can be seen from one angle, still this should give a pretty good impression of the different DML set-ups. The 3D plots are shown with a frequency resolution from 100Hz to 10.000Hz, as this is the interesting area for speech.

Figure 18 shows that the response is relatively overall flat with one exciter. At 90° the dipole directivity is marked as a blue area.

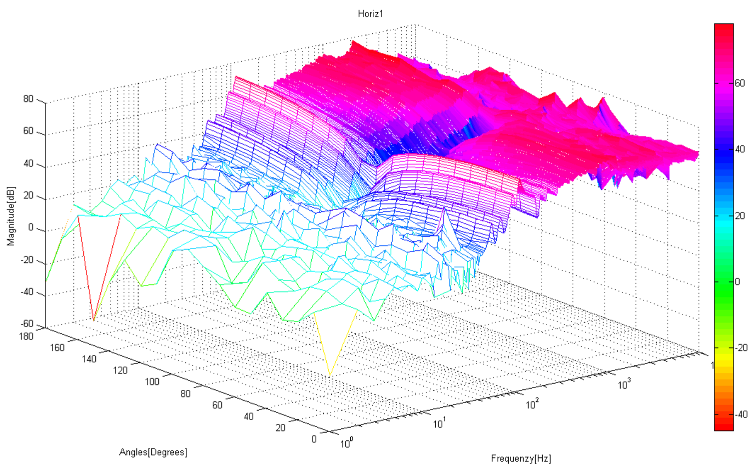

Figure 18: Frequency response viewed as a function of angle, measured Horizontal with one Exciter 8Ω

The set-up with two exciters, Figure 19, is very different from previews set-up. One can see the same characteristics as in the polar plot, Figure 13, the interference and out-phasing is spread throughout over the whole response and gives bad audible conditions.

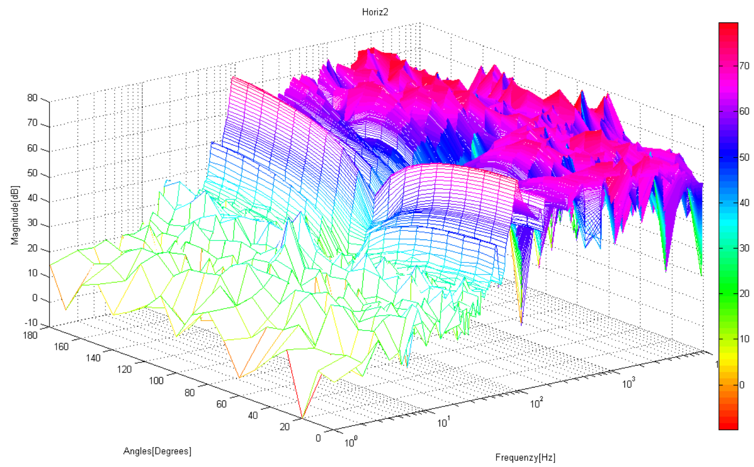

Figure 19: Frequency response viewed as a function of angle, measured Horizontal with two Exciters, 16Ω

With three exciters, Figure 20 show that the response is not as flat as with one exciter, which can be seen in Figure 18. There are many dips in the frequency response and unevenness in magnitude.

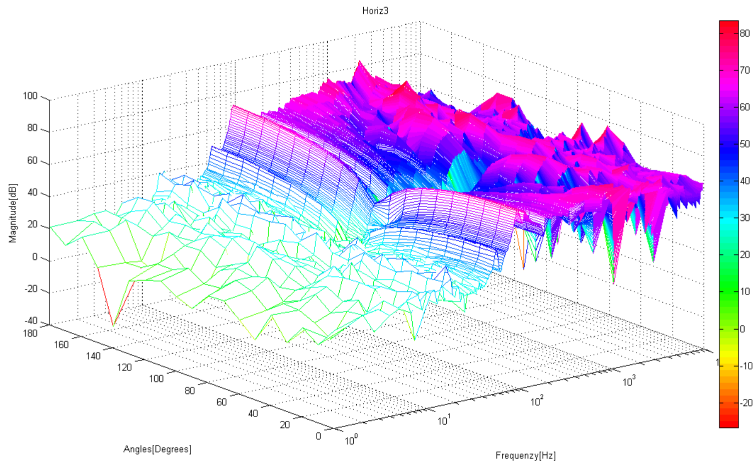

Figure 20: Frequency response viewed as a function of angle, measured Horizontal with three Exciters 24Ω

4.4 3D Plots: Vertical Plane

As mentioned in section 4.2.2, the 3D figures below should show a clear dipole directivity. The horizontal plane will determine the audio quality in altitude as the audience are sitting around the office table.

Figure 21 shows a the response with one exciter. The dipole directivity is possible to see, and the response is pretty flat.

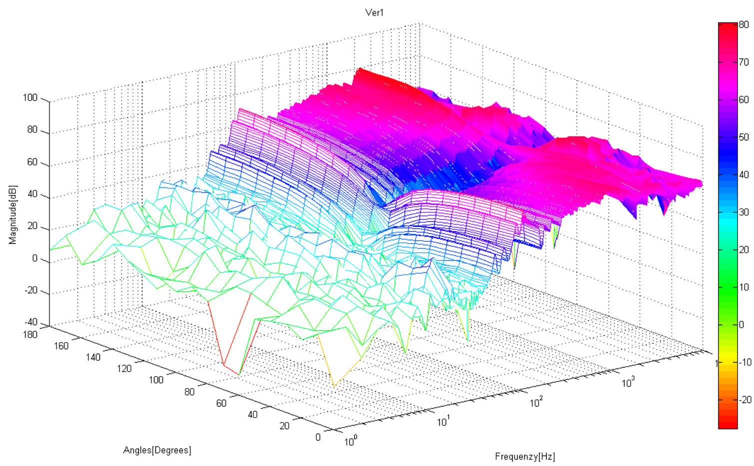

Figure 21: Frequency response viewed as a function of angle, measured Vertical with one Exciter 8Ω

With two exciters the response is not as symmetric as the previews, but the dipole directivity is more noticeable, see Figure 22.

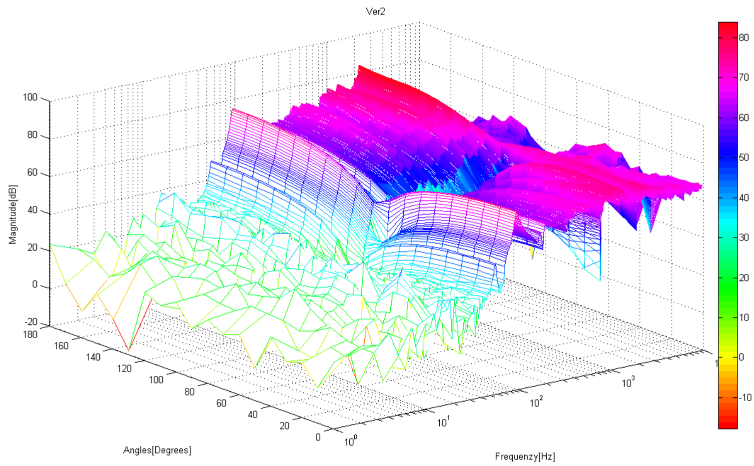

Figure 22: Frequency response viewed as a function of angle, measured Vertical with two Exciters 16Ω

The set-up with three exciters have the most flat response overall in this plane, but still have some big dips in magnitude at some frequencies, see Figure 23. When looking back to Figure 17, the dipole directivity was reduced from the set-up with two exciters, this is not easy to tell in this plot, and seems to be just as good as in the previews plot, Figure 22.

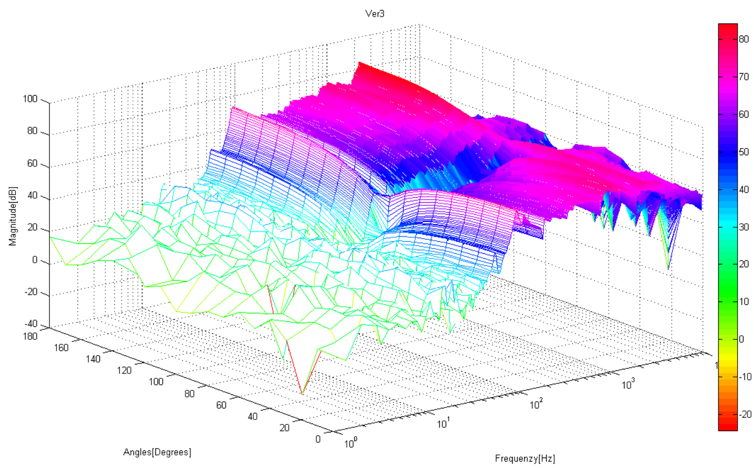

Figure 23: Frequency response viewed as a function of angle, measured Vertical with three Exciters 24Ω

4.5 Two Exciters mounted on opposite sides and out of Phase

It was attempted to put two exciters one at each opposite side of the panel, this solution was cancelled after the first measurement in a anechoic chamber. The reason why this conclusion was made can be studied in Figure 24.

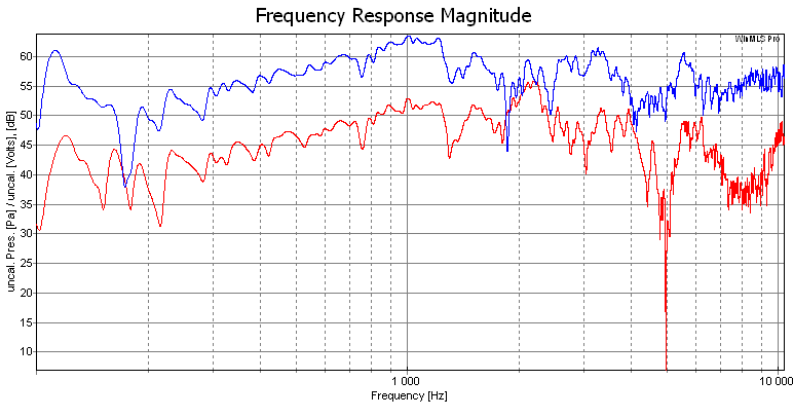

Figure 24: Two Exciters mounted on opposite sides and out of Phase [Red] compared with one exciter [Blue],

4.6 Subjective Listening Test

A subjective test was conducted with six statements, where the subjects had to rank the DML speaker compared to the standard PC-Speakers as seen in Appendix E in a video-conference room, "Studio" at NTNU. There were a total of 19 participants, 9 participants who were placed in "Position 1" and 10 participants were placed in "Position 2", referring to Figure 25. The room has pretty good acoustical properties with an reverberation time of 0.62s and dimensions 5.67 x 5.77 x 2.78 meters. The recommendations of section 2.8.1 was used in this test. The set-up for the subjective test can be viewed in Figure 25.

The test material was a 15 second high resolution video-clip of a person talking. The subjects were sitting on a 45° angle from the DML and the screen, and the head turned towards the screen. The video-clip was played at each speaker set-up, then the subjects gave their answer to two the statements. This procedure was repeated until all statements were answered. This method was chosen because the recommendations in Section 2.8.1 suggested that when testing audio, the short memory of the audio test-clip should be evaluated.

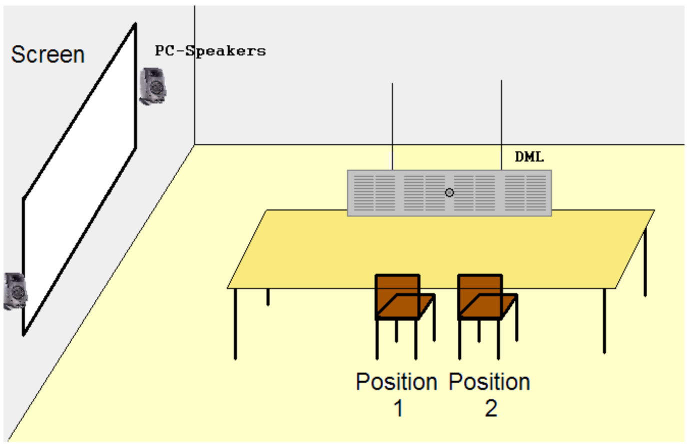

Figure 25: Setup at the listening test

The six statements to test if the DML work better as a video conference speaker than a standard PC-Speaker set-up was:

- "The first impression of the DML was better"

- "The speech-intelligibility of the DML was better"
- "The sound from the DML was more natural"
- "It was not uncomfortable that the sound did not come directly from the screen"
- "The fact that the DML was so close gave me more closeness to whom speaking to"
- "I would use the DML for a long video-conference"

In the subsections below 4.6.1 to 4.6.6 the results of each statement is shown, the last subsection shows the average opinion and rating for all the statements, section 4.6.7. The two positions in Figure 25 were calculated individually as well, since the listening experience for each position can be different. As mentioned in 4.6, the subjects head was facing the screen from both positions. The subjects sitting near the screen were getting the sound from the DML manly at one ear. The direction can be described as a little bit "from behind". The subjects sitting far from screen were getting the audio from the DML more distributed to both ears. The direction of the sound can be described as "45° from the side".

The following graphs have a rating on the x-axis, the words have bin shorted, to clarify the meaning; "S.Worse" means "Slightly Worse", "No op" means "No opinion" and "S.Better" means "Slightly Better".

4.6.1 "The first impression of the DML was better"

This statement was made to get a quick overview which set-up the subjects preferred the best, before analyzing each property of the DML. Figure 26 shows that the first impression of the DML was a bit mixed. A tendency of a few subjects sitting near the screen experience to dislike the DML compared to the PC-Speakers. Overall, the mixed results seem to vary in listening positions and audio preferences. No one regarded the DML as a clearly better speaker set-up.

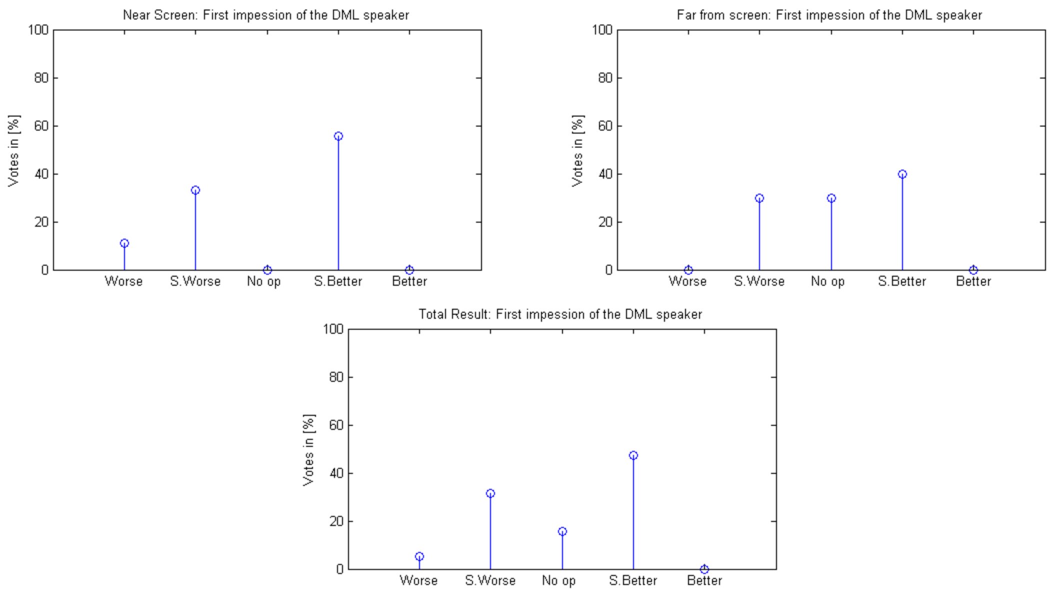

Figure 26: Graph: First impression of the DML

4.6.2 "The speech-intelligibility of the DML was better"

To verify if the DML has a better speech-intelligibility compared to the PC-Speakers, this statement was answered by the participants. This property is very important to have efficient communication in a video-conference. If one study the subjects sitting near the screen in Figure 27, no-one thought the DML had worse speech-intelligibility than the PC-Speakers, and over 20% thought it has better speech-intelligibility. The ones sitting far from the screen had bigger variation, 30% of them was experiencing the DML to have slightly worse speech-intelligibility. But 20% answered that the DML had better speech-intelligibility. Overall the majority of the subjects experienced the DML to have better or slightly better speech-intelligibility.

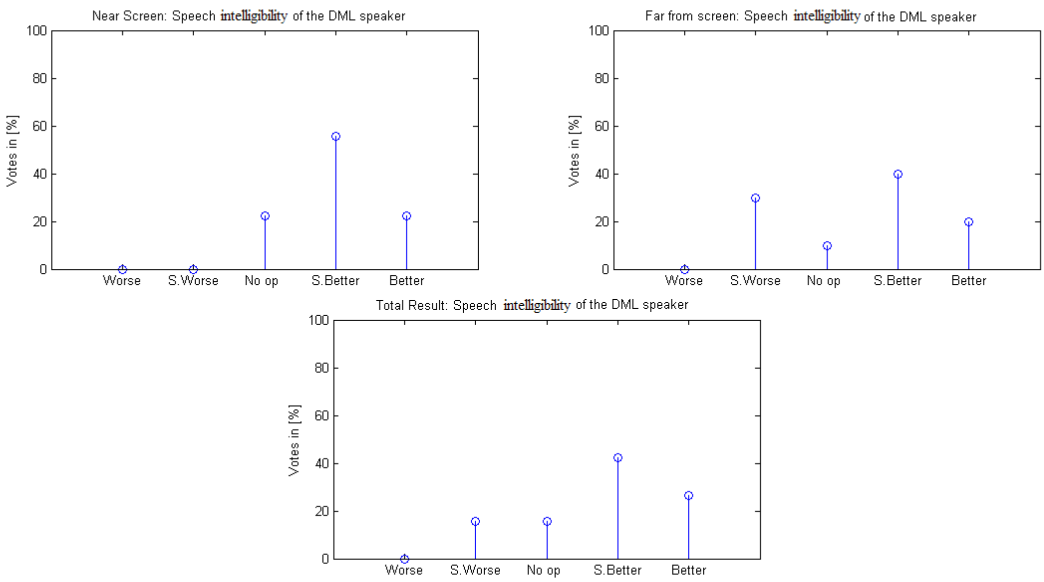

Figure 27: Graph: Better speech-intelligibility

4.6.3 "The sound from the DML was more natural"

This statement was chosen to test if the DML has a natural and realistic sound. Figure 28 shows the subjects sitting close to the screen has a big variation of what they thought was the more "Natural" speaker. One see also those who are sitting far from the screen, and the total results, has mixed opinions on which speaker has the more "Natural sound".

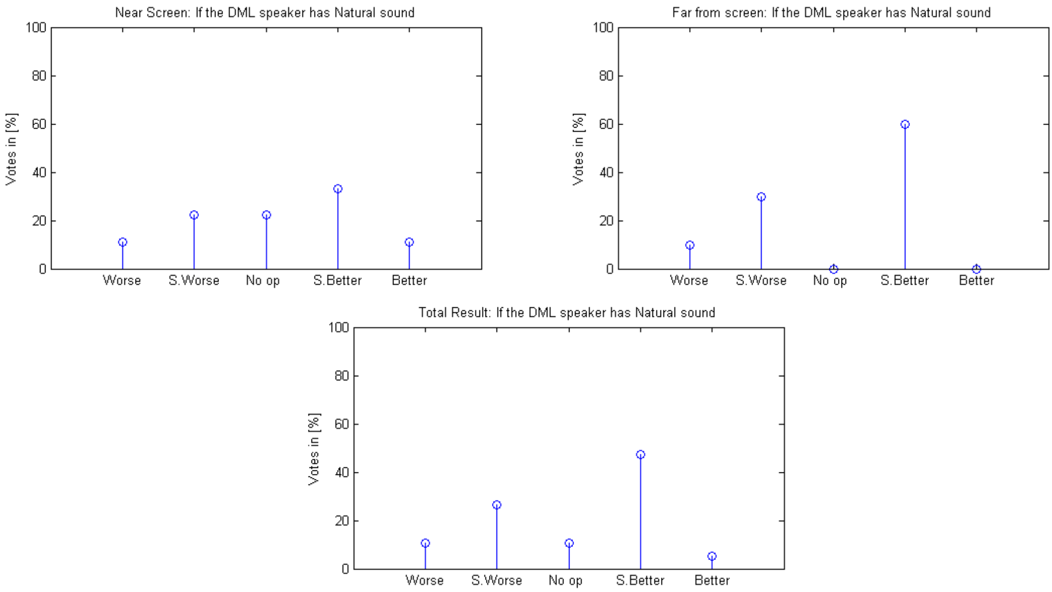

Figure 28: Graph: Subjects who felt them DML had a more natural sound

4.6.4 "It was not uncomfortable that the sound did not come directly from the screen"

When subjects facing the screen, the sound from the DML came from a different direction than the video-picture. As described in Section 4.6, the subjects sitting far from the screen might have a audio advantage, especially on this criteria. As seen in Figure 29, the ones sitting far from the screen seem to do not mind the sound not coming from the screen. This was also the majorities opinion.

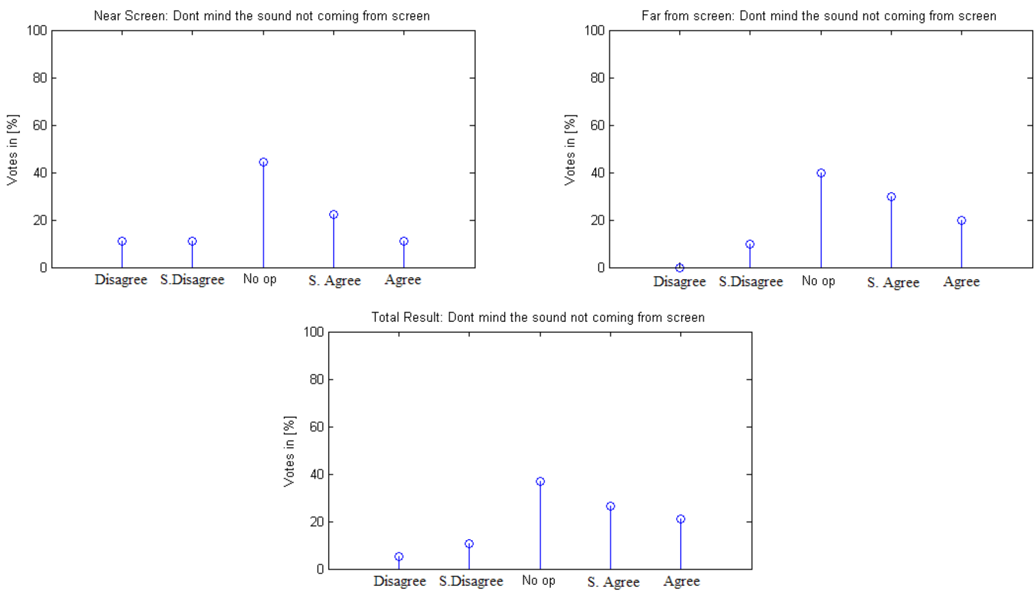

Figure 29: Graph: Did not mind sound not coming from the screen

4.6.5 "The fact that the DML was so close gave me more closeness to whom speaking to"

This statement was chosen to test if the DML gave a better virtual closeness in the video conference. The results can be seen in Figure 30. There is a tendency of the ones sitting close to the screen have no opinion on this statement. The ones sitting far from screen clearly seem to agree that they feel more closeness to the voice coming from the DML. Overall no-one thought the closeness was worse on the DML.

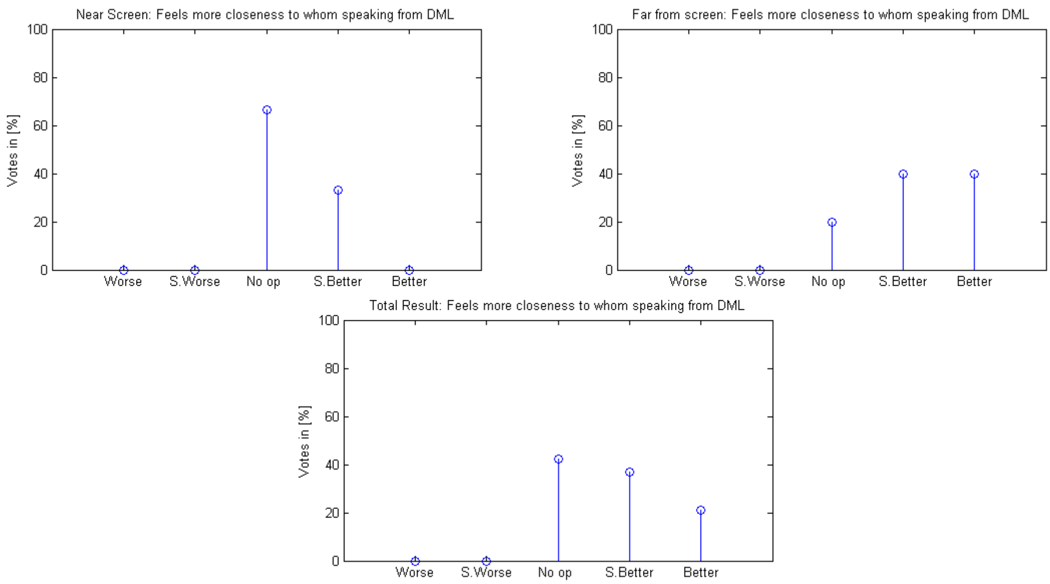

Figure 30: Graph: Subjects who felt they got closeness to whom speaking

4.6.6 "I would use the DML for a long video-conference"

This statement is a kind of a summary if the subjects really prefer the DML in a video conference. The results in Figure 31 show that the majority of the subjects sitting close to the screen would "Slightly More" prefer the DML in a long video conference. The results from the subjects sitting far from the screen have the same result, just with a bigger variance. In overall it is about only 30% of the subjects which would not prefer the DML in a video conference.

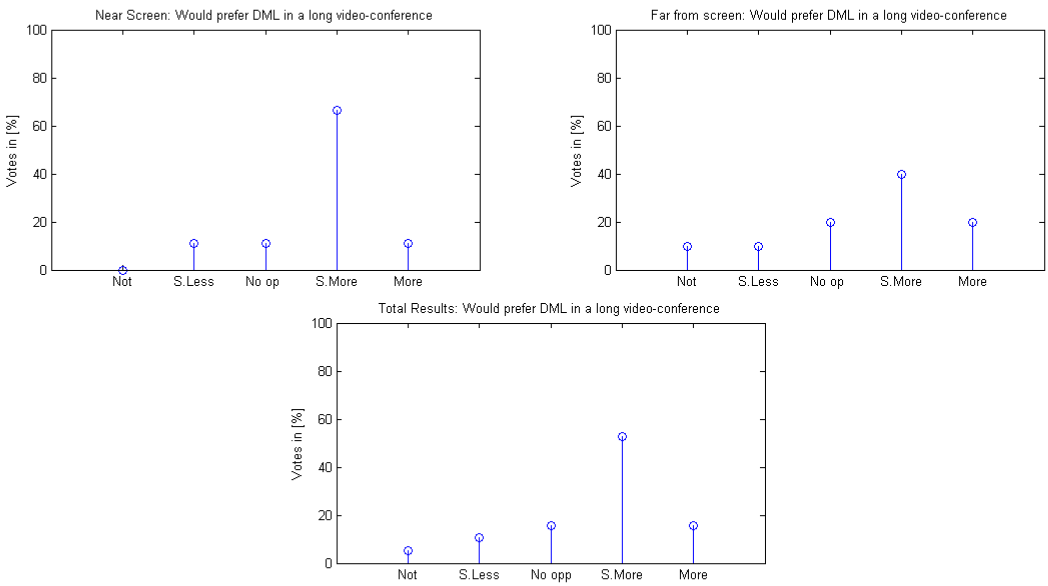

Figure 31: Graph: Subjects who would prefer the DML in a long video-conference

4.6.7 Average Results

In Figure 32 the different properties of the DML is rated from a scale from 1 to 5. The middle line is the limit if the subjects did not prefer or preferred the DML compared to the PC-Speakers. Figure 32 shows that all statements were agreed by the majority of the subjects, that the DML is better than the PC-Speakers. From the top, "Closeness" was the best property of the DML with almost 4 out of 5. The second best property is the "Speech-intelligibility" which is ranked very close to "Closeness". The third place is that the subjects would prefer the DML in a "Long Video-conference". Fourth from the top is the property that the "Sound Not from Screen" was not uncomfortable. On fifth place the sound from the DML is more "Natural", and is ranked about 3 out of 5. Last place is the "First impression" of the DML compared to the PC-Speakers, also ranked about 3 out of 5.

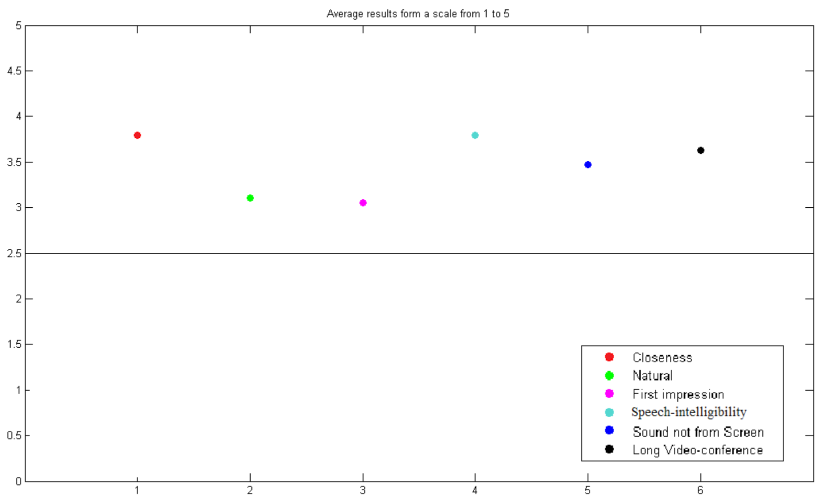

Figure 32: Average of the subjective test from a scale from 1 to 5

5 Discussion

5.1 Designing and Construction

Starting construction the DML, the first thing to do was to cut the panel in half. The original panel was 120cm x 60cm x 0.4cm meter and with a slot width of 0.2mm, see Appendix D. This was considered too large to mount over a office table, since it should not cover the vision of the audience. The new measures on the panel is 120cm x 30cm x 0.4cm. Contact glue was used to mount the three exciters to the panel, if the exciters are not glued properly there will be a lot of resonances. Since the whole panel is a radiator, the solution to avoid any influence on the sound while measuring, was to construct a custom-built stand that does not stop the movement in the panel. The exciters are from the high-end company Elac, see Appendix A.

The micro slots have as described in Section 3.1 good acoustic properties, the difference in flexural rigidity make the modes in the panel distribute more evenly. This benefits to positive qualities such as a more even polar frequency response [1]. Without the micro slots there will be more standing waves internally in the panel and this will lead to strong cam-filter effects such as dips in frequency response, as a consequence of out- phasing, also opposite effects will occur as resonance peaks.

5.2 Measuring the DML

The measurements were done, as mentioned before, in a anechoic chamber by mounting the custom built stand on a electrical rotating engine which was controlled by a script in MatLab. When the DML was mounted to the custom stand, a sine sweep was played to measure the frequency response. Then by using the MatLab script the DML was rotated 10° and the procedure started over again until the DML was rotated and measured 180° . It was used a omni directional microphone, see Appendix C,

5.2.1 Polar Frequency Responses

The polar response plots in Section 4.2, Figure 12, 13, 14, 15, 16 and 17, the difference in magnitude is easy to see. Since these are just some randomly chosen frequency this can not fully represent the polar response, but give a comparison foundation of the magnitude of each frequency and symmetry of the different set-ups. For all set-ups a common property is that there are uneven and unsymmetrical responses for 2000Hz and 4000Hz.

5.2.2 3D Plots

The assumption that three exciters would give a more efficiency and better dipole effects was made in Section 2. Figure 18, 19 and 20 shows the 3D plot in the horizontal plane. One can make the comparison and see that the difference is not mainly in magnitude, as three exciters are not that more efficient than one. The dipole effect in the low frequency area are bigger with three exciters, but more uneven than with one. Overall, three and two exciters have more dips and out-phasing than with just one exciter.

Studying same 3D plots in the vertical plane in Figure 21, 22 and 23, the difference in the polar frequency response is not big, as the number of exciters gets higher. Only the dipole directivity gets better in the low frequency area and the theory in Section 2 seem to fit very well. The magnitude difference increases a little as the number of exciters increase. Even since the efficiency is a bit better with more exciters, the argument is too poor as the cost of the DML will be a lot higher and will never pay off, if the bad response in the horizontal plane is not considered.

From the 3D polar plots, especially in the vertical plots (see Figure 21 for an example), one can see at some frequencies the SPL is higher at the backside of the DML. The backside is defined as the side where the exciter is mounted. This is most likely because the exciter itself adds energy to the SPL.

The frequency spectrum which is interesting is from 80Hz to 8000Hz, as the main purpose of the DML is speech, so frequencies aside this is not considered important for the properties of this DML. The best polar frequency response was the setup with only one exciter as in the 3D plots, Figure 18 and 21. This setup was used when doing the subjective tests and is considered the final prototype.

The drastic fall in magnitude under 100Hz is a disadvantage, as one can see from the 3D plots, example seen in Figure 18. One can see from Figure 12 that the 100Hz response is 10dB lower than the 1000Hz. This can make the sound have some lack of the bass in especially male voices. With little low frequency sound, a long video conference can fatigue the listeners and be a uncomfortable experience.

The set-up with two exciters with one on each side of the DML, and wired out of phase did not give the wanted effect, as seen in Section 4.5 in Figure 24. The purpose was to gain a high SPL without change the polar frequency response. One reason the result did not work as good as intended might be a inaccuracy when mounting the exciters, that leading to cause mechanical difficulties when it radiates.

5.2.3 Subjective Test

The word "Natural" can maybe be a bit undefined word to each individual subject as the results have such a big variation. From the subjective test in Figure 32, the two worst properties of the DML is the "Naturalness" of the sound and the "First impression". One reason for this might be a weak low frequency response, and a sub-woofer might be useful to get more pleasant listening experience, even this might not necessarily contribute positive attributes to the speech-intelligibility.

The speech-intelligibility of the DML had some very good results. This is not necessarily because the DML have a better polar frequency response, but the position of the DML have big advantages as written in the theory section 2.7. The fact that the DML is so close to the audience as described in Section 1.3, seem to work very well. Every subject thought that the DML gave more closeness to the person talking in the video-conference as one can see in Figure 30 in Section 4.6.5.

The majority of the subjects agreed that it was not uncomfortable that the sound did not come from the screen. As Figure 29 in Section 4.6.4, there is a clear difference in the subjects sitting near the screen and far from screen. As described in Section 4.6 the ones sitting near the screen get the sound from the DML a little from behind, this seem to be a factor if one study Figure 29.

To avoid this problem another DML should be mounted between the subjects sitting near the screen and the screen. In lager video conference meetings with a large audience, more DML's have to be used to cover all the listeners. If one study Figure 12, one can see that after 60° the response from the DML gets uneven and gives bad conditions for a good listening experience.

The last statement was as mentioned to be a conclusion if the subjects preferred the DML compared to the PC-Speakers. It shows the majority preferred the DML compared to the PC-Speakers when one look at Section 4.6.6, Figure 31.

In Section 4.6.7 an overview of the different statements are seen, and their results in Figure 32. The best properties of the DML from the subjective test is "Closeness" and "Speech-intelligibility" and the position of the DML seem to work as predicted. The worst properties are if the sound was "Natural" and the "First impression". This might be because it did lack some low frequency power, and gave a "unnatural" sound that did not give a good first impression.

Feedback from many of the subjects from the subjective test were; "The DML has a lack of bass, this can make it a little uncomfortable to listen to, especially in a long video conference" - Acoustician's & Hi-Fi Audiophile's.

5.3 Improvements and further work

The micro slots make the modes in the panel split up. A good suggestion would be to make slots around the panel to split up standing waves in the panel even more.

Since the use of this DML is video conferencing applications, mounting a microphone under the DML to minimize the radiation from the panel can be a good idea. Since microphones can measure both sound pressure and sound velocity, precautions have to be made when choosing positions and microphone type.

There should be done some more work by increasing the low frequency power from the DML by using other exciters or different techniques. The set-up in Section 4.5 should be tested with better accuracy.

6 Conclusion

The DML with more than one exciters did not benefit to the polar frequency response due to out-phased frequencies. More exciters did increase the dipole directivity, and gained a little effect on the DML, but none of these properties make it worth having more than one exciter. With only one exciter the polar frequency response is very good from 100Hz to 5000Hz, and descent from 5000Hz to 8000Hz. The response under 100Hz has a low SPL, and with use of a exciter with better power in the low frequency area, this would make a great DML for video-conferencing applications.

Using two exciters, one on each side of the DML, and wiring them out of phase did not work, and gave a very bad SPL. This should be further investigated with a better accuracy when mounting the exciters.

The subjective test was done with only one exciter, since this gave the best response. Since the PC-speakers were mounted on the wall, near the ceiling corners, they excited strong room-modes and gave a bad speech-intelligibility as seen in the results in Section 5.2.3.

From the subjective test conclusions can be drawn; the best properties of the DML in this scenario is that it gives good "Closeness" to the one speaking. It also have good speech-intelligibility. The ones not minding the sound not coming from screen, as it was playing from the DML scored close to the previews properties. The use of the DML in a long video conference scored "not as good". The two worst properties were the first impression and the "Naturalness" of sound. Still, the majority liked the DML better then the PC-Speakers in all test-statements.

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[10] Line Arrays: Theory and Applications
Mark S. Ureda
JBL Professional, Northridge, CA USA
Presented at the 110th Convention
2001 May 12-15 Amsterdam, The Netherlands

[11] Gjenskapning av kildekarakteristikk ved hjelp av nærfelts akustisk holografi
Norges teknisk-naturvitenskapelige universitet Institutt for elektronikk og telekommunikasjon.
Trond Blesvik, Juni 2010

[12] Design Guidelines for Practical Near Field Line Arrays
James R. Griffin, ph.D.

[13] Dipole Loudspeaker Response in Listening Rooms
James M. Kates
Cirrus Logic, Boulder, CO 80301, USA
J.Audio Eng Soc. Vol.50, No.5 2002 May

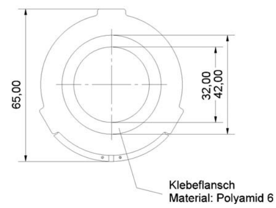
A Elac Exciter 3720KST1

ELAC

37 mm EXCITER

Autotune Exciter 3720 KST

Artikel-Nr. 83003 ohne PTC / without PTC-Fuse (only on request)
Artikel-Nr. 83005 mit PTC / with PTC-Fuse (standard)

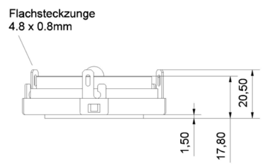


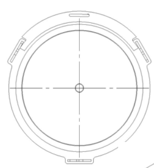
SPECIAL FEATURES

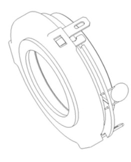
- aluminum voice coil former
- 37 mm voice coil diameter
- high efficiency due to strong neodym magnet
- high power handling capacity
- on-board PTC-Fuse (83005)

SPECIFICATIONS

z_n	rated impedance	8 Ω
R_{DC}	dc-resistance	6,5±0,3 Ω
P_N	nominal powerhandling	20 W (depending on application)
SPL	sensitivity (dB/W/m)	depending on Application
-	total weight	170 g
-	maximum displacement	+/- 0,5 mm
-	material of voice coil former	Al
-	material of voice coil wire	Cu
d	voice coil diameter	37,6 mm
f_{res}	resonance frequency	620 Hz
M_{MS}	moving mass (incl. air)	3 g
B●l	effective force factor	5,2 T●m
B^2●l^2/R_{DC}	electromagnetic damping	4,2 kg/s
C_{MS}	compliance	0,023 mm/N

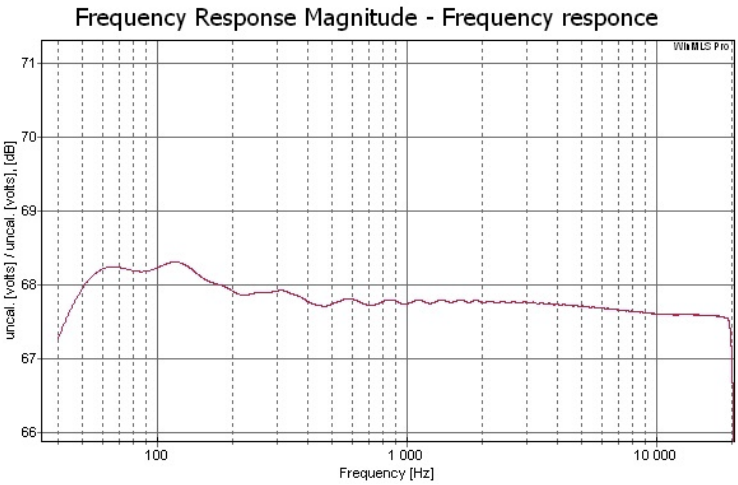






ELAC Electroacustic GmbH, Rendsburger Landstr. 215, 24113 Kiel
Tel +49 (0)431 64 77 4-0 www.elac.com / info@elac.de

B QUAD 50E amplifier frequency response

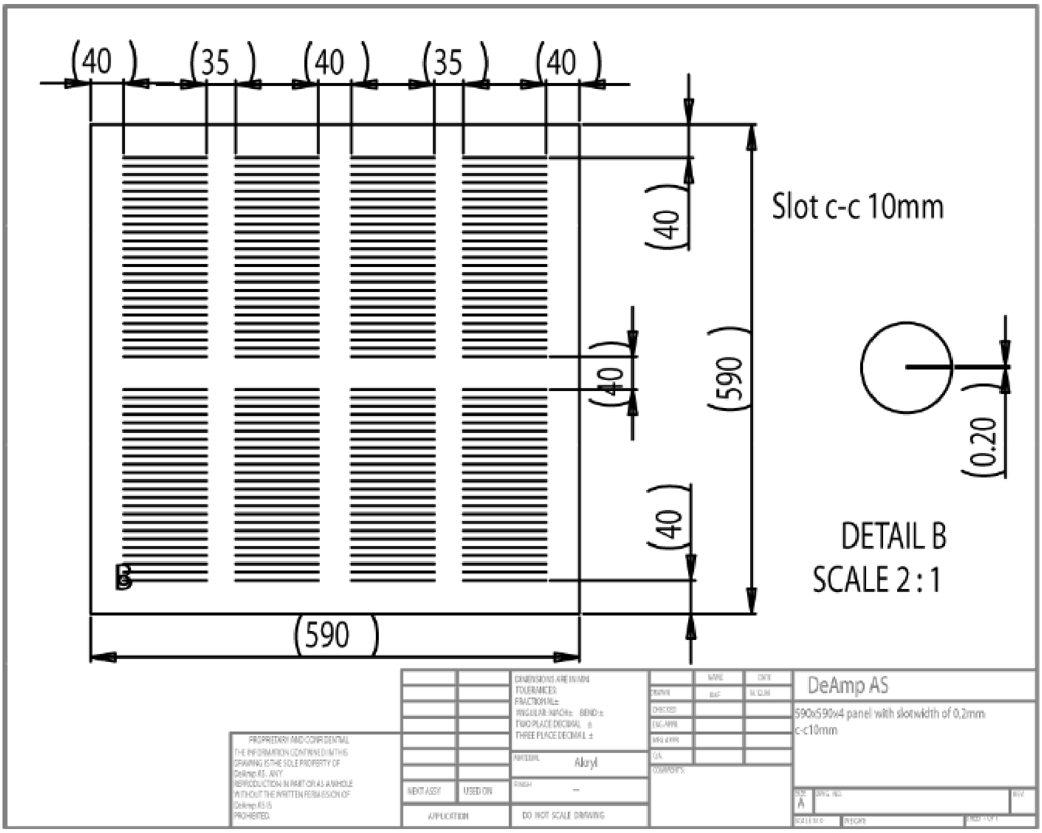


C Microphone and Microphone Pre-amplifier

Microphone:

- Microphone Pre-amplifier: Norsonic 1201 – 30517
- Bruel & Kjær
- Free-field 1/2"
- Type 4165
- BC- 2113
- Serial Number: 2068937
- Open-circuit Sensitivity, S_0: -26 dB re 1V/Pa
- Equivalent to 47.5 mV/Pa
- Uncertainty, 95% confidence level: 0.2 dB
- Capacitance: 19.8 pF

D DeAmp Acrylic Panel



Mass density	1170 kg/m^3

E Polk Audio Atrium 45p

polkaudio® the speaker specialists®

Atrium 45p

9-1/2" H x 6-1/4" W x 7-5/8" D
(24.13cm H x 15.88cm W x 19.37cm D)

Specifications

Driver Complement	
Mid/Woofer	1 – 4-1/2" Diameter (11.43cm) Dynamic Balance, mineral filled Polymer with rubber surround
Tweeter	1 – 3/4" Diameter (1.91cm) Soft dome with Neodymium magnet
Electrical	
Overall Frequency Response	60Hz – 20kHz
Recommended Amplifier Power	n/a w/channel
Inputs	5-way binding post speaker-level inputs and coaxial (RCA) line level inputs
Outputs	5-way binding post speaker-level output to passive
Dimensions	
Cabinet Size	9-1/2" H x 6-1/4" W x 7-5/8" D (24.13cm H x 15.88cm W x 19.37cm D)
Mounting Options	90 degree swivel bracket supplied
Enclosure Type	Sealed
Built-in Power Amplifier Specs	
Power Output	25 watts Continuous Average Output

Serial Number: ATRIUM45p 1409W