Optimization of Aspect Ratio and Material Parameters of a DML Membrane

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Introduction

A Distributed Mode Loudspeaker (DML) is a loudspeaker system which is distinguished from a conventional loudspeaker by the acoustic radiation that originates from uniformly distributed, free bending wave vibration induced in a stiff, light membrane [1]. The frequency response of a DML is predominantly conditional to the selection of membrane materials, dimensions, and exciter positioning. To improve the performance of a DML, various kinds of methods have been proposed [2]. The methodologies to modify the frequency response includes the addition of a subwoofer [3], attached mass method [4-6] and optimizing the exciter positioning [7], the variation of thickness [8] and varying the length of component beams [9]. Amongst other factors, the frequency response of a DML depends on the mode distribution of the membrane. This study focuses on this aspect.

Firstly, experimental modal analysis is performed on two materials with different geometrical properties. A simulation model of the membrane is developed and mode fitted. The simulation software *wave6* is used for this study [10]. An introduction to mode distribution is presented and a criterion is introduced for describing the mode distribution. The criterion is further used to compare membrane materials based on their geometrical parameters i.e. aspect ratio and the material properties i.e. level of anisotropy. Finally, the results and discussions are summarized.

Modal Analysis

Natural frequencies and corresponding mode shapes are obtained through experimental modal analysis. The experimental setup consists of a roving impact hammer, accelerometers and the membrane placed in a way that it is decoupled to the system supporting it. Two membrane materials are used to validate the material fitting process. Both the materials have their outer boundary fixed to a frame. The dimensions of material A is 612 x 490 x 3.17 mm with aspect ratio 1.25 and material B is 765 x 382.5 x 3 mm with aspect ratio 2. Experimental modal analysis is performed using the roving hammer method where a roving hammer is used for the force introduction and accelerometers to measure the resulting vibrations.

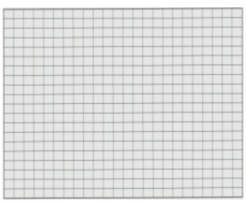
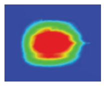
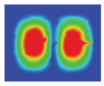
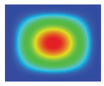
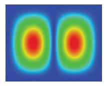
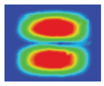
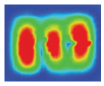
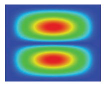
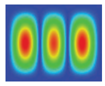
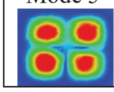
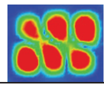
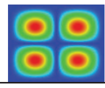
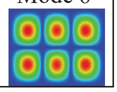


Figure 1: A DML membrane with meshes on the surface.

To obtain material properties, a simulation model is created with similar geometry and boundary conditions. Then the model is further used to fit the modes obtained through measurements. The material properties are varied in the simulation model until the modes from the measurement results and simulation results fit with the least percentage difference as shown in figure (2). This is performed for both the membrane materials and the mode shapes are shown in the table (1).

Table 1: Measurement and Simulation mode shapes for membrane material A with aspect ratio 1.25

Measurement		Simulation	
Mode 1	Mode 2	Mode 1	Mode 2
			
Mode 3	Mode 4	Mode 3	Mode 4
			
Mode 5	Mode 6	Mode 5	Mode 6
			

The main aim of this task is to validate the working of the simulation model and the expected percentage error. Since constructing a membrane with varied material properties, in reality, is a time-consuming process, simulation technologies are used. Simulation technologies provide the possibility to investigate the effect of material parameters on the modes and their distribution.

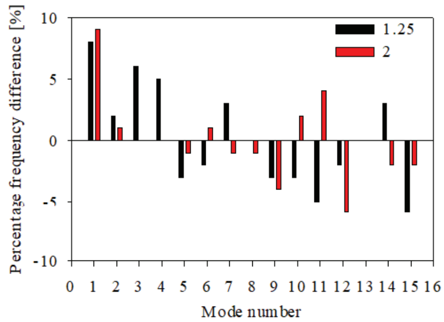


Figure 2: Percentage difference between the fitted simulation and measurement modes for the two-membrane materials A (aspect ratio 1.25) and B (aspect ratio 2).

Mode Distribution

Modal density is defined as the number of modes in the given frequency range [11-13]. In theory, the modal density of materials varies depending on their boundary conditions and the relationship considers the length and width of the plate from the point of its fixed boundary attachment [14]. [14] also suggests that the difference between the theoretical and analytical results at 1000 Hz are 26%. However, these criteria rely on the number of modes in the frequency range and don't take either the uniform distance between the modes or the perceptuality of sound into consideration.

Mode Distribution Criteria

The distance between the modes is vitally important to describe the mode distribution. This ensures that the modes are equally spaced contributing to the linear frequency response. Hence the preference is given to the uniformity of distance between the consecutive modes. Figure (3) shows the natural frequencies of the same material with different aspect ratios. Aspect ratio refers to the ratio between the length and width of the membrane. The material properties and thickness are fixed throughout. A logarithmic scale is used in the frequency analysis since the perception of sound is based on the logarithmic scale.

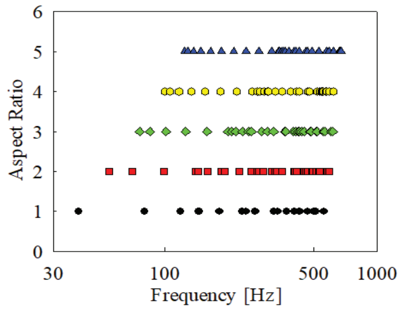


Figure 3: Location of modes for membrane materials with different aspect ratios.

To measure the difference between the frequencies of two modes, octaves are used. Octaves are the logarithmic unit for ratios between frequencies. One octave equal doubling the frequency [15]. Octave distance is calculated using equation (1) and is used to describe the distance between the consecutive modes.

$$number\ of\ octaves, n = \frac{\log(f_2/f_1)}{\log 2} \tag{1}$$

From figure (3), it is seen that modes at higher frequencies are closer to one another. Hence the octave distance at higher frequencies will be considerably lower than at lower frequencies. The range of interest lies in the first few modes since its contribution to the resulting frequency response is higher.

The average of these octave distances is considered, and this value is referred by the term *Average*. This indicates how close or far the modes are placed from one another. A low value means that the modes have small distances between them. Inversing the *Average* would result in the number of modes in an octave in the frequency range considered. To take into account the uniformity of the distance, standard deviations of the octave distances are considered. This term is referred to as *Deviation* and a lower value represents that the modes are uniformly distributed. These two factors help in deriving the mode distribution. An octave ratio is defined as a distribution criterion, where a high value represents better mode distribution and is given by equation (2). The factor of *Average* and *Deviation* is inversed to reduce the complexity of digits after the decimal point.

$$Octave\ ratio = \frac{1}{Average\ \times Deviation} \tag{2}$$

Optimization of Aspect Ratio

The octave ratio is used to optimize the aspect ratio. All other material parameters are kept constant. First 10 modes are used for this study. Figure (4) illustrates the natural frequencies and the criteria ratio for varying aspect ratio. It is seen that as the aspect ratio increases, the first natural frequency and the criteria ratio increases. In other words, better mode distribution can be obtained at higher aspect ratios, but the lower frequencies are compromised. The frequency range of interest has to be taken into consideration and a better mode distribution for that particular range can be selected using the criteria.

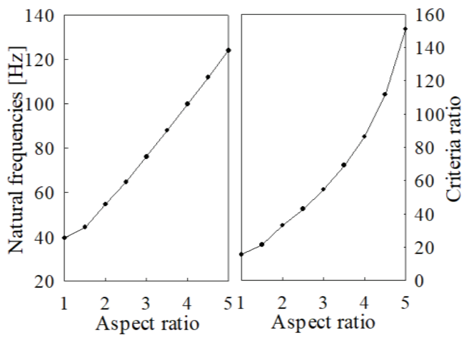


Figure 4: Comparison of Natural frequency and Criteria ratio for membrane materials with different aspect ratios.

To investigate the selection of aspect ratio further, it is significant to inspect the factors separately. Figure (5) shows the *Average* and the *Deviation* of the octave distance for different aspect ratios. It is seen that the slope of the *Deviation* curve is high until aspect ratio 2. But after this, the slope reduces comparatively. This means that an aspect ratio of 1 and 1.5 has a higher deviation and it is not preferred when in comparison with aspect ratio 2. However, this is a trade-off between the low frequencies and the mode distribution. Preference has to be made based on the design considerations. On this basis, this criterion is utilized to find out the better mode distributed aspect ratio for the frequency range of interest.

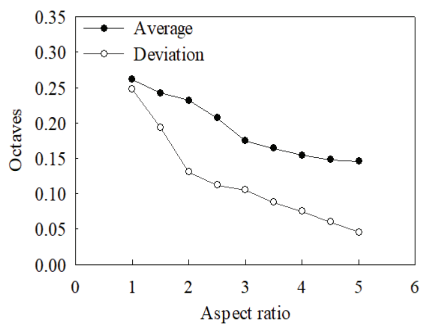


Figure 5: The Average and Deviation criteria values for the different aspect ratio of membrane materials.

This criterion is further used to verify the simulation and measurement mode distribution. The table (2) shows the factors and the criteria ratio calculated for the simulation and measurement modes and they are in close coordination with one another. The results are presented for both the aspect ratios. This suggests that the simulation model is validated and the criterion is applicable for both simulations as well as measurements.

Table 2: Comparison of criteria values between measurement and simulations

Factors	Aspect ratio 1.25		Aspect ratio 2	
	Measurement		Simulation	
Average	0.31	0.30	0.24	0.23
Deviation	0.21	0.22	0.12	0.12
Criteria ratio	15.3	15.1	34.7	36.2

To validate the optimization results further, experiments to measure the Sound Pressure Level (SPL) for the aspect ratios 1.25 and 2 are performed and the results are shown in the figure (6). The membrane is excited with an exciter which is mounted at 1/3rd of the membrane length and width. SPL is measured with a microphone which is placed at a 2m distance from the membrane. The membrane is made to rotate in the range of -90° to +90° and SPL is measured for every 10° and then integrated. The SPL of aspect ratio 1.25 characterizes low dips which are shown in black circles. These dips are avoided in the aspect ratio 2, due to the reduced distance between the consecutive modes. There is a slight shift in the first mode and the distribution however overcomes the low dips, contributing to the linear response relatively. Hence, by suitable selection of the aspect ratio of the membrane, the frequency response is improved.

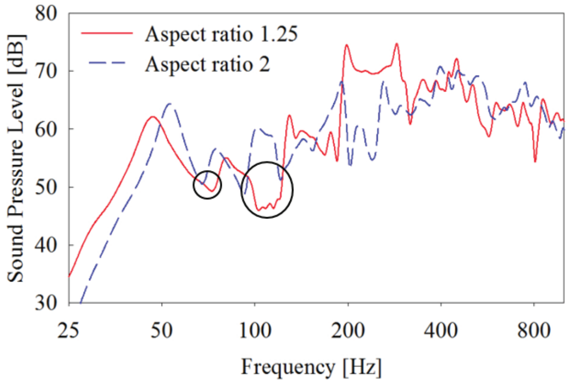


Figure 6: Frequency response for membrane aspect ratios 1.25 and 2 when exciter placed at 1/3rd of the length and width.

Optimization of Material Properties

The study above is based on isotropic materials. To optimize the material property on the basis of mode distribution, anisotropic material properties are considered. First 20 modes are considered for this study. Anisotropic materials have different material properties in different directions. For a 2D element in the simulation model, however, this depends on only two directions i.e. x and y-direction. The properties, Young's modulus in x (E_x), Young's modulus in y (E_y), the shear modulus in xy and poison's ratio in xy have a high influence on the stiffness of membrane material. Shear modulus is calculated from Young's modulus and Poisson's ratio, according to Huber's equation [16-17]. So the independent properties include E_x and E_y. *Level of anisotropy* or *Anisotropic levels* is the ratio between E_x and E_y [18]. It represents the amount of anisotropy in the material and is given in equation (3).

$$Level\ of\ Anisotropy, l = \frac{E_x}{E_y} \tag{3}$$

Level of anisotropy is varied by simultaneously reducing young's modulus in one direction and increasing in the other direction, thereby ensuring that the overall global stiffness of the material remains the same and is given in the equation (4).

$$E_x = E \cdot \sqrt{l} \qquad\qquad E_y = \frac{E}{\sqrt{l}} \tag{4}$$

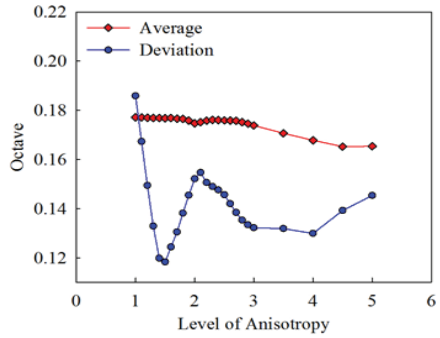


Figure 7: The Average and Deviation criteria values for different anisotropic levels of membrane materials.

The figure (7) shows the Average and Deviation values plotted for varying anisotropic levels for a square plate i.e. aspect ratio 1. It is seen that the material with anisotropic level 1.5 possesses less deviation than isotropic material. When the design requirement is a square plate, an anisotropic material with level 1.5 can be used to obtain better mode distribution.

More number of aspect ratios, as well as various levels of anisotropy, are considered for this study and a few of them including 1.5, 2.5, 3.5 and 5 are presented here. From figure (8), it is seen that the isotropic material possesses higher octave ratios for aspect ratios greater than or equal to 1.6. As the aspect ratios increase above 1.5, the mode distribution always remains better when isotropic material is used. An anisotropic material, however, isn't suitable for these cases considering the mode distribution. However, for aspect ratios less than 1.6, there is a high degree of variation in the mode distribution and it can be concluded that the anisotropic level has a high dependency on the mode distribution. For example, for an aspect ratio 1.2, an anisotropic material with level 1.5 is better. For aspect ratio 1.4, an anisotropic material with level 2.5 is better. Hence, improvements on the mode distributions can be achieved in this range with the use of suitable materials.

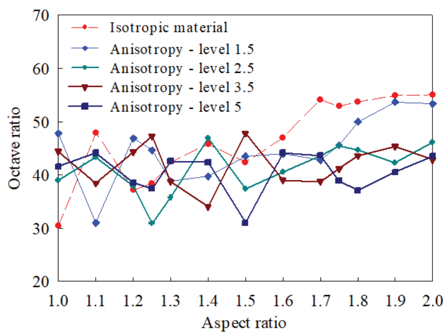


Figure 8: The Average and Deviation criteria values for aspect ratio 1 to 2.

Figure (9) considers similar results for aspect ratios ranging from 2 to 5. Here it is further made evident that isotropic material has better mode distribution for higher aspect ratios.

It is also seen that as the anisotropic level increases, the mode distribution gets worse and its extent depends on the level of anisotropy. As the aspect ratios of membrane materials become higher, the anisotropy levels should be as low as possible to obtain better mode distribution.

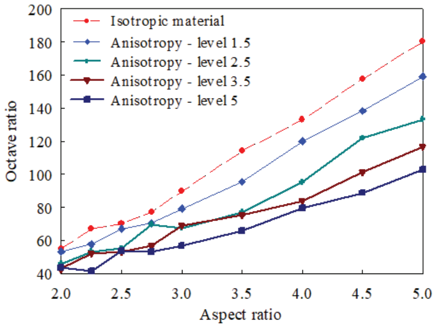


Figure 9: The Average and Deviation criteria values for aspect ratio 2 to 5.

Results and Discussions

The main aim of this work is to optimize the mode distribution which affects the linear frequency response of a DML. The goal lies in developing a criterion which is used to compare materials based on the mode distribution. The average and the standard deviation of the octave distance between the modes describes the uniformity of mode distribution. Octave distance is used since it depicts the perception of sound. Based on this criterion it is realized that increasing aspect ratios results in increasing criteria ratio and natural frequency. Hence it becomes important to compromise between the lower frequencies and the mode distribution based on this criterion. This is achieved by focusing on the frequency range of interest. However, a trade-off between them is important to attain a better aspect ratio for the material. From the results, it is seen that the material with aspect ratio 2 is selected considering the trade-off. As discussed before, the selection relies on the design considerations of the loudspeaker and the desired frequency range.

To optimize the material property, comparisons are made based on the level of anisotropy. The geometrical parameters and the stiffness of the material are fixed throughout this investigation. Comparison of materials based on their anisotropy level reveals that when the aspect ratio increases above 1.5, an isotropic material always possesses better mode distribution. When in case of low aspect ratios than 1.6, care must be taken in choosing the material since they possess high dependency on the level of anisotropy. This further provides the possibility to optimize the membrane materials depending on the aspect ratios desired. With the help of this criterion, it becomes possible to optimize membrane geometry and anisotropy levels based on the mode distribution.

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