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Extraction of Characteristics Quantities and Electro-Technical Modeling of Electrodynamic Direct Radiator Loudspeaker

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Abstract— This paper documents a comprehensive study of loudspeaker modeling to propose such a model that could be used for dimensioning the driver element of an electrodynamic direct radiator loudspeaker system. A lumped-parameter model for such a driver element mounted in an infinite baffle is presented after being derived from careful consideration of the physical principles related to the electro-mechano-acoustic transduction mechanism of the driver element under inspection. Different characteristics quantities such as resonance frequency, Q-number, acoustic efficiency at maximum radiated sound power, frequency response and electrical impedance were extracted from the models representing the loudspeaker driver elements of diameter 8”, 16” and 32”. Subsequently the outcomes were compared and their behaviors verified with the help of extensive simulation results.

Index Terms— Characteristics quantities, Comparison, Electro-technical modeling, Electrodynamic Loudspeaker, Lumped parameter model, SPICE, Simulation, 8” and 16” and 32” loudspeaker driver.

1 Introduction

To perform mechanical work is amongst one of the very important field of application of electrical energy. The phenomena regarding the force that originates related to electrical and magnetic field are the ones that are usually get exploited for such application of electrical energy. But amongst these two, the forces originating from magnetic fields are technically are of more importance. The distinction that one usually makes here are the one between current forces that originate from the interaction between different current paths, e.g. forces between two current carrying conductors and forces that act between different magnetic conductors that carry magnetic flux. These lead one to talk about current forces and reluctance forces. In certain cases the combination of these types of forces is used. The modeling of loudspeaker is deemed to be important for its ability to dimension an apparatus that utilizes such forces and the access to such a model that describes the actual magneto-mechanical transduction proves to be a valuable resource where an electric model defines the behavior of an electro-mechanical device in a circuit. Loudspeaker is a type of transducer which incorporates three level of transduction termed as electro-mechano-acoustic transduction, i.e. they convert electrical energy into mechanical energy, which in turn is converted into acoustic energy.

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2 Description of Modeled Objects

2.1 Physical Quantities of the Loudspeaker

- **Drive coil diameter**: It is the diameter of the speaker coil wound around a paper or aluminum which is set on a permanent magnet.
- **Drive coil breadth**: It is the thickness of the coil.
- **Membrane diameter**: It is the diameter of the membrane of the speaker which is attached to the coil and pivoted to the suspension of the speakers.
- **Number of drive coil turns**: It is the number of coil turns is the voice coil of the speaker.
- **Wire diameter in the drive coil**: One of the factors that indicate the power of the speaker is the wire diameter. Thicker wire can carry heavy current, increasing the power output of the speaker.
- **Spring constant of the membrane suspension**: It defines the range of the speaker membrane displacement without rupturing the speaker membrane.
- **Mass of the membrane and the drive coil**: Mass of the membrane and the drive coil affects the C_{mass} in the equivalent circuit of loud speaker and can also increase the gain at low frequencies.
- **Equivalent mechanical damping of the membrane, drive coil and suspension**: It is constant for the loud speaker that its membrane will come to rest after 1 second if a force of 1 Newton is applied and it displaces the membrane to 1 meter.
- **Magnetic Flux density in the pole gap**: The permanent magnetic flux density also defines the power of the loud speaker output. As strong as the magnet flux density it will increase the power output.

2.2 Lumped Parameters

- **r_e**: The electrical resistance of the drive coil.
- **L_e**: The electrical inductance of the drive coil.
- **L'_e**: Leakage inductance of drive coil, taken as 1μH.
- **L_{comp}**: The electrical equivalent model of suspension of the membrane of the loudspeaker taken as $b^2l^2c_m$.
- **R_{damp}**: The electrical equivalent model for the effect of damping of membrane and drive coil is a resistive phenomenon which can be calculated as $(b^2l^2)\ c_m$.
- **C_{mass}**: The electrical equivalent model for the mass of the loudspeaker membrane and coil taken as $m / (b^2l^2)$.
- **R_{damp}**: The electrical equivalent of the power radiated from the loudspeaker and is modeled as a resistance that can be calculated as $(b^2l^2) / (\rho cA)$.
- **C_{damp}**: It is the electrical equivalent of the damping occurs because of air pressure on the face of load speaker this can be calculated as $(8a\rho A) / (3\pi b^2l^2)$.

3 Modeling of Loudspeaker Drivers with Diameter of 8", 16" and 32"

3.1 Design Parameters

Modeling means the process of organizing information about a given system which is in our case an electrodynamic loudspeaker and the said information obtained by analysis of the physical system at a fundamental level, yet involving approximation sufficient to simplify the model into an approachable form. To start analyzing system the key physical quantities needs to be measured beforehand. For the cases presented here which comprises of three samples of loudspeaker drivers which were designed to deliver output of frequency ranging from base to mid-range, those key physical statistics were measured and presented in the Table 1.

TABLE 1
PHYSICAL QUANTITIES MEASURED FOR LOUDSPEAKER DRIVERS WITH DIAMETER OF 8", 16" AND 32"

Symbol	Quantity	8″	16″	32″
d_d	Drive coil diameter (m)	0.0677	0.135467	0.270933
L	Drive coil breadth (m)	0.0067	0.013333	0.026667
d_m	Membrane diameter (m)	0.2032	0.4064	0.8128
N	Number of drive coil turns	31	61	123
d_w	Wire diameter in the drive coil (m)	0.00165	0.00165	0.00165
k_u	Spring constant of the membrane suspension (N/M)	2916	1458	729
m	Mass of the membrane and drive coil (Kg)	0.00987	0.136533	1.092267
d	Equivalent mechanical damping (Ns/m)	13.333	26.66667	53.33333
B	Magnetic flux density in the pole gap (T)	0.9	0.9	0.9

m = meter, N = newton, Kg = kilogram, s = second, T = tesla.

3.2 Calculation of Lumped Parameters

Analogies can be very convenient for conducting analysis in unexplored fields. By dint of analogies an unfamiliar system may be compared with one that is better known. In this case the known being the realm of electrical circuits governed by Kirchhoff's and Ohm's law which can help to sidestep the analysis of motion of mechanical systems like loudspeaker. By careful use of analogies, from the parameters measured directly from the loudspeaker driver elements under inspection, the values of the lumped parameter components that comprise the electrical equivalent model of the transducer were calculated by equating them into the basic formulae regarding the electrical resistance and inductance while incorporating the physical elements from the electrical domain of the electro-mechano-acoustic transducer. While producing the analogical models for the mechanical and acoustic components in the transducer the concept of mobility analogy was employed, which can be found gracefully explained in the early texts like Beranek [1]. While developing the model of the transducer advanced modeling approximations suggested by Watkinson [2] was also taken into account. Finally for calculating the radiation impedance presented by the air medium to the diaphragm of the electrodynamic loudspeaker driver, the approximations presented by Engdahl and Edin [3] were accepted.

Table 2 documents a detailed list of the mathematical models of the electrical, mechanical and acoustic components playing key roles in the electro-mechanic transduction process of loudspeaker system.

TABLE 2
MATHEMATICAL MODELS FOR THE LUMPED COMPONENTS USED IN THE ELECTRICAL EQUIVALENT CIRCUIT MODEL

Symbol	Description	Formula
R_{wire}	Electrical resistance of the drive Coil (Ω)	$\frac{4\rho(N\pi d_d)}{\pi {d_w}^2}$
L_{coil}	Electrical inductance of the drive coil (H)	$\pi d_d N^2 \times 10^{-7} (log \frac{4d_d}{L}-0.5)$
L_{lead}	Leakage inductance of coil (H)	Constant (1μH assumed)
L_{comp}	Electric model of suspension of diaphragm (H)	$B^2l^2c_m = \frac{B^2(N\pi d_d)^2}{k_u}$
C_{mass}	Electrical model of the mass of the diaphragm (F)	$\frac{m}{B^2l^2} = \frac{m}{B^2(N\pi d_d)^2}$
R_{damp}	Electric model of damping of diaphragm (Ω)	$\frac{B^2l^2}{r_m} = \frac{B^2(N\pi d_d)^2}{d}$
C_{rad}	Electric model of acoustic resistance (F)	$\frac{\rho}{B^2l^2}\frac{8a}{3\pi}A$
R_{rad}	Electric model of acoustic compliance (Ω)	$\frac{B^2l^2}{\rho cA}$

ρ = resistivity of the material of the coil = 1.72×10^{-8}(For Annealed Copper), Ω = ohm, H = henry, F = farad.

Now equating the sets of equation given in the Table 2 with the values of the measured quantities from the Table 1 it is very easy to find the magnitudes of the lumped parameter components which will form the final electrical equivalent model of the transducer, which is in the case presented is an electrodynamic direct radiator loudspeaker.

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TABLE 3
LUMPED PARAMETERS CALCULATED FOR LOUDSPEAKER DRIVERS WITH DIAMETER OF 8", 16" AND 32"

Symbol	8″	16′′	32′′
R_{wire}	0.0677	0.135467	0.270933
L_{coil}	0.0067	0.013333	0.026667
L_{lead}	0.2032	0.4064	0.8128
L_{comp}	31	61	123
C_{mass}	0.00165	0.00165	0.00165
R_{damp}	2916	1458	729
C_{rad}	0.00987	0.136533	1.092267
R_{rad}	13.333	26.66667	53.33333

3.3 Equivalent Circuits

As the magnitudes of all required lumped parameters are calculated, they can be used to form the electrical equivalent model for the transduction process of an electrodynamic loudspeaker. Formation of the equivalent circuit was done by the rules dictated by the admittance analogy. So it can be seen in the circuits that the lumped components representing the mechanical and acoustic components of the loudspeaker are connected in parallel with the source while the components derived from the electrical domain remains in series.

Fig. 1 shows the implementation of the equivalent circuits in popular SPICE software, PSpice where it can be seen that the modeled equivalent software is being feed with an AC source of magnitude 12V and output at the acoustic impedance element is being traced by voltage and current probe.

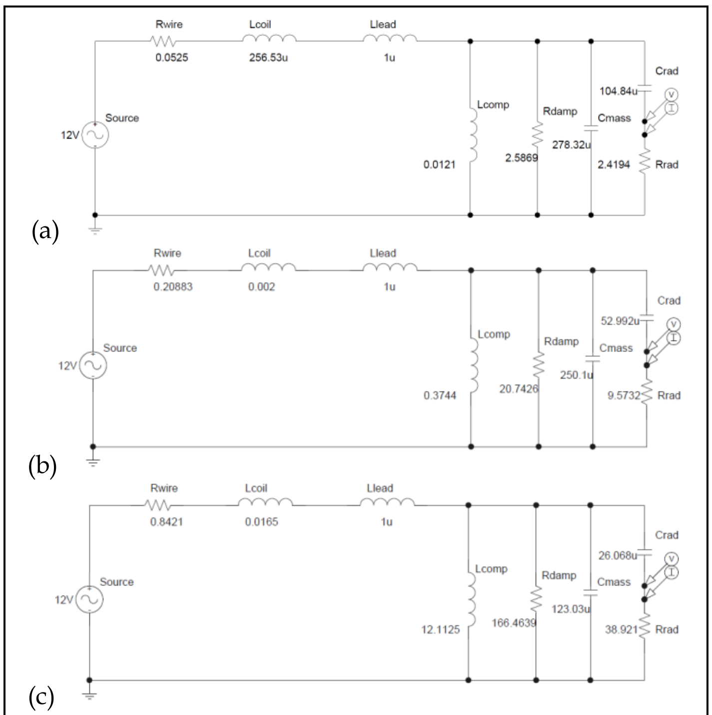

Fig. 1. Equivalent circuit of electrodynamic loudspeaker drivers of diameter (a) 8", (b) 16" and (c) 32" modeled in PSpice.

4 EXTRACTION OF CHARACTERISTICS QUANTITIES

Following characteristics quantities were extracted by simulating the derived model of the electrodynamic loudspeaker with the help of simulation software PSpice.

4.1 Resonance frequency

It is the frequency f_{res} for which the power radiated by a system which is in this case a loudspeaker, is maximum. To obtain the output power characteristics of a loudspeaker using the equivalent model, the power across the radiating component in the model needed to be determined. The radiating components of the derived model happens to be R_{rad} which is modeled as a resistance and to get the power across this component the voltage and current across R_{rad} needs to be determined first. Fig. 2 shows the voltage and current characteristics of loudspeaker of different river diameter at frequency ranging from 1μ Hz to 2.5k Hz.

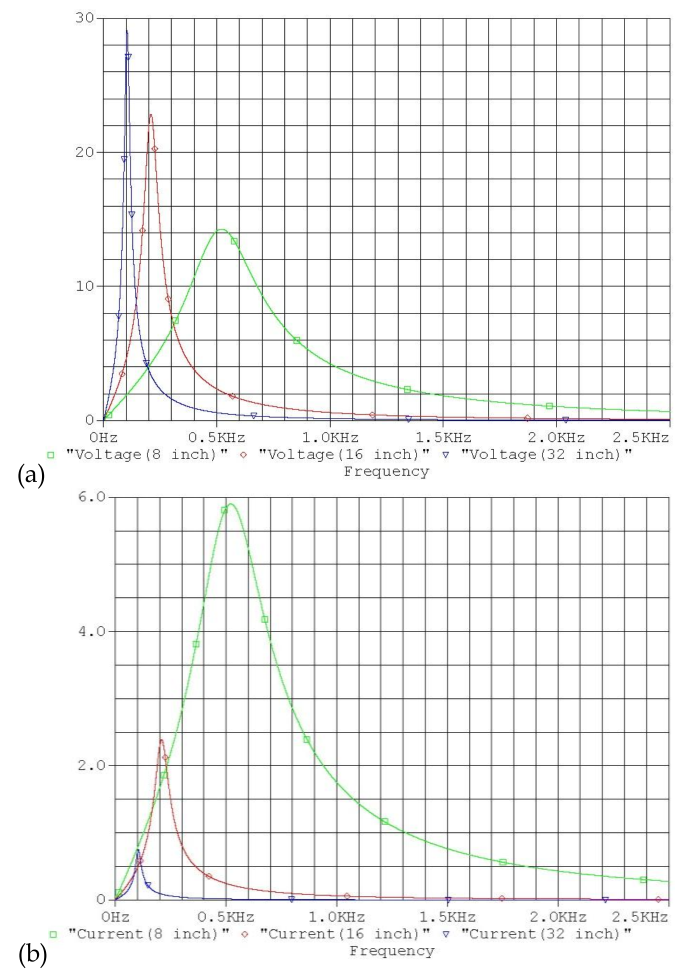

Fig. 2. Plot of (a) output voltages and (b) output currents in PSpice.

The output power characteristic of the loudspeaker was found by multiplying the voltage and current. Fig. 3 shows the output power characteristic obtained by aforesaid process. The peak values for the curves were found which gave the frequency at the maximum radiated power which is indeed the resonant frequency, f_{res} and was documented in the Table 4.

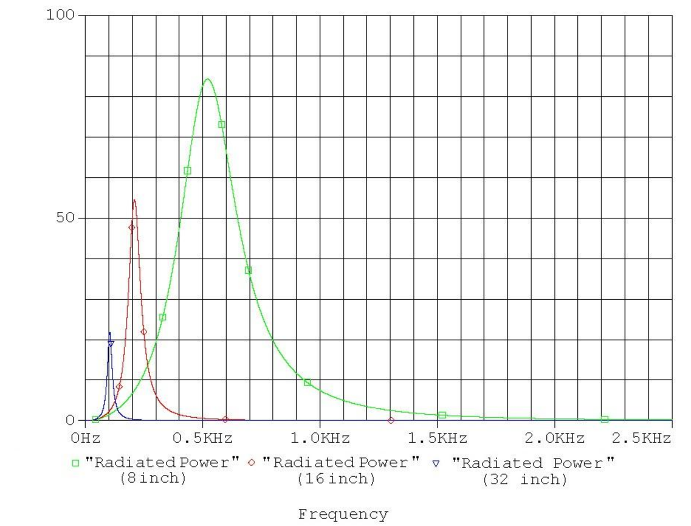

Fig. 3. Plot of output acoustic power for loudspeaker drivers with different diameters in PSpice.

4.2 Q factor

Q factor is the degree of selectivity or narrowness of the frequency response as is defined as follows -

$$Q = \frac{F_{res}}{f_1 - f_2} \quad where \quad f_1 > f_{res} \; and \; f_2 < f_{res}$$

Here f_1 and f_2 are the frequencies at which the radiated power is half of the power radiated at resonant frequency, f_{res} that is $0.5P_{max}$. Using the aforementioned equation Q factor for all three cases of loudspeakers were calculated and subsequently documented in the Table 4.

4.3 Acoustic efficiency

Efficiency is the ratio of output power to the input power. So to determine the efficiency the input needs to be calculated first. The input power drawn by the electrodynamic loudspeaker was found by multiplying the input voltage and current to the loudspeaker driver. Fig. 4 shows the plot of output power characteristics over the frequency range of 70 - 2.5k Hz.

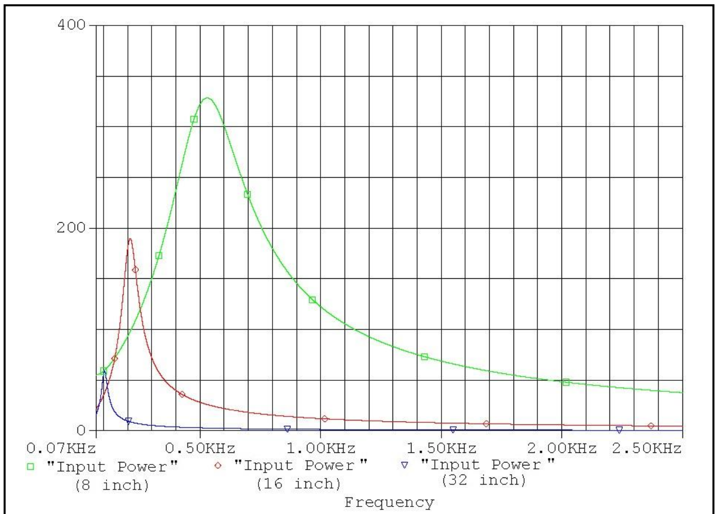

Fig. 4. Plot of input electric power for loudspeaker drivers with different diameters in PSpice.

After getting waveform of both input and output power, the efficiency can be calculated easily by dividing the output power by the input. Fig. 5 shows the graph obtained by the aforementioned process for the acoustic efficiency.

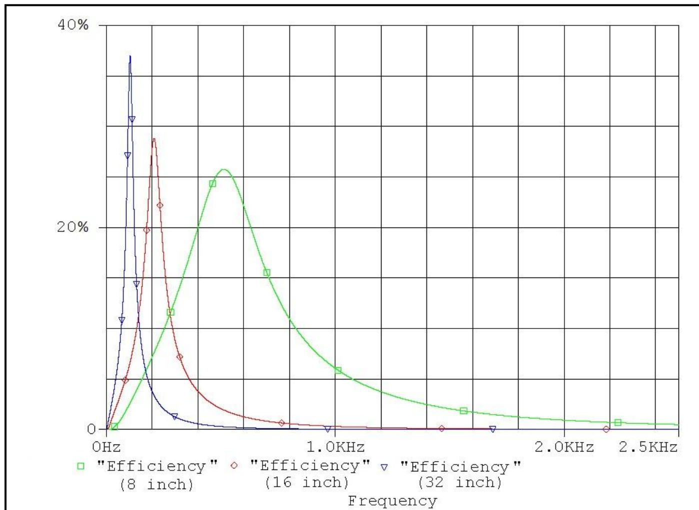

Fig. 5. Plot of acoustic efficiency for loudspeaker drivers with different diameters in PSpice.

4.4 Frequency response

The frequency response can be represented in a form of sound intensity level which as per specification of ANSI S1.8-1969[4] is given by the expression, $L_w = 10Log_{10}(P/P_o)$ where P is the radiated sound power and P_o is the reference power equal to 10^{-12} W. Fig. 6 shows the graph obtained by the means of the aforementioned equation of intensity in the frequency range of 10 - 1k Hz in semi-log scale.

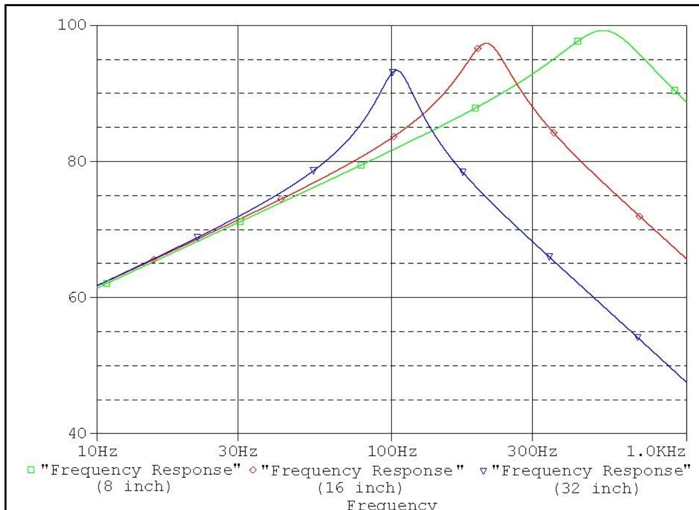

Fig. 6. Frequency response for loudspeaker drivers with different diameters in PSpice.

4.5 Electrical impedance

The electrical impedance can be found by the application of Ohm's law i.e. by dividing input voltage by input current. Fig. 7 shows the graph obtained for electrical impedance by aforesaid process at frequency range of 1 - 10k Hz in full logarithmic scale. From the graph electrical impedance at the frequency of 1k Hz was measured and documented in the Table 4.

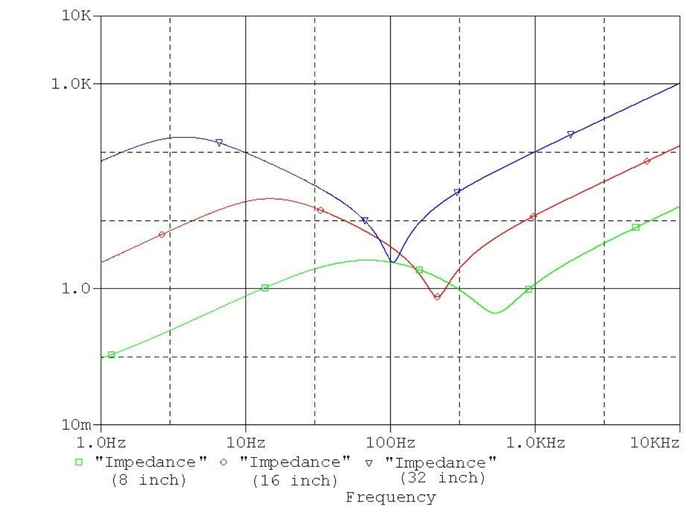

Fig. 7. Plot of electrical impedance for loudspeaker drivers with different diameters in PSpice.

5 Comparison Between Loudspeaker Drivers

TABLE 4
COMPARISON BETWEEN RESULTS FROM LOUDSPEAKER DRIVERS WITH DIAMETER OF 8”, 16” AND 32”

Parameters	8″	16′′	32′′
Maximum power radiated	122.469 W	54.569 W	21.796 W
Resonant frequency	554.086 Hz	209.232 Hz	103.849 Hz
Q factor	2.008	3.36	4.264
Maximum efficiency	15.73%	28.80%	37.02%
Efficiency at resonant frequency	15.72%	28.79%	37.01%
Electrical impedance at 1k Hz	0.489Ω	11.956 Ω	102.398 Ω

W = watt, Hz = hertz, Ω = ohm.

Table 4 documents a quantitative comparison of the characteristics quantities extracted from the simulation of the derived electrical equivalent circuit of the loudspeaker.

Apart from these quantitative relations some qualitative relation can also be observed from plots of the characteristics quantities shown in the last section. Notable amongst such qualitative relations is the trend in change in magnitude of the characteristics quantities with the change of the drive diameter. In all the cases the trend is found to be exponential in nature.

By observing the trend in the comparative plotting of efficiency for loudspeaker drivers of different diameters, it can be predicted that perfectly efficient transduction can only be achieved if the drive is infinitely wide.

Also by noticing the trend in the relative plotting of frequency responses of loudspeaker drivers of different diameters it can be seen that at low frequency region loudspeaker of all size produces sound of similar intensity.

6 Discussions

From the quantitative comparison shown in Table 4, it can be seen that the Q-number, maximum efficiency and electrical impedance were increasing with the increase in diameter of loudspeaker driver element. However, the maximum power radiated and resonant frequency and electrical impedance were found decreasing with the increase in diameter of loudspeaker driver element. This work also proves that the maximum efficiency does not coincide with the resonant frequency which can be clearly seen in the quantitative comparison in Table 4.

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