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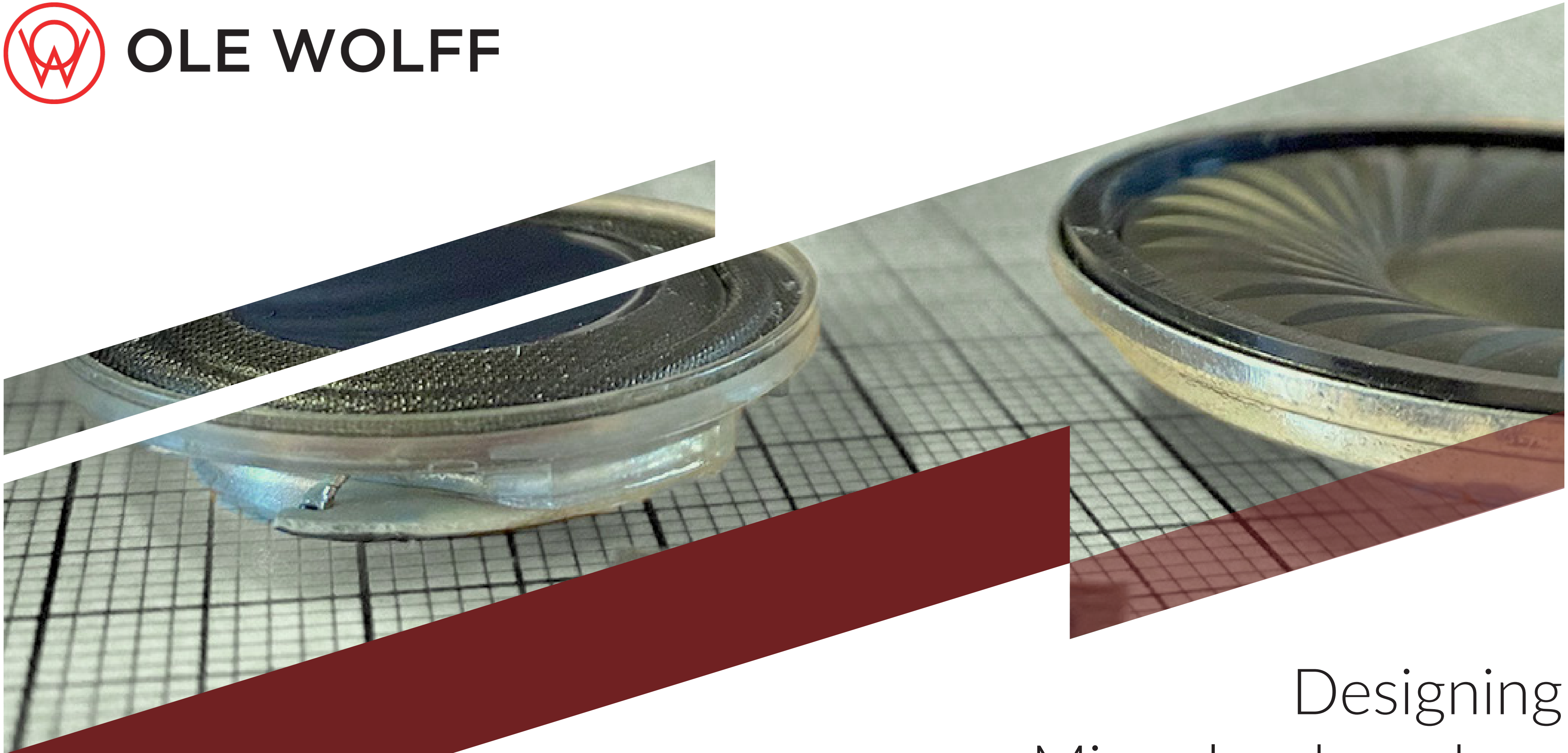


Designing Micro loudspeakers for Portable Devices

Part I - The Linear Model

WP03

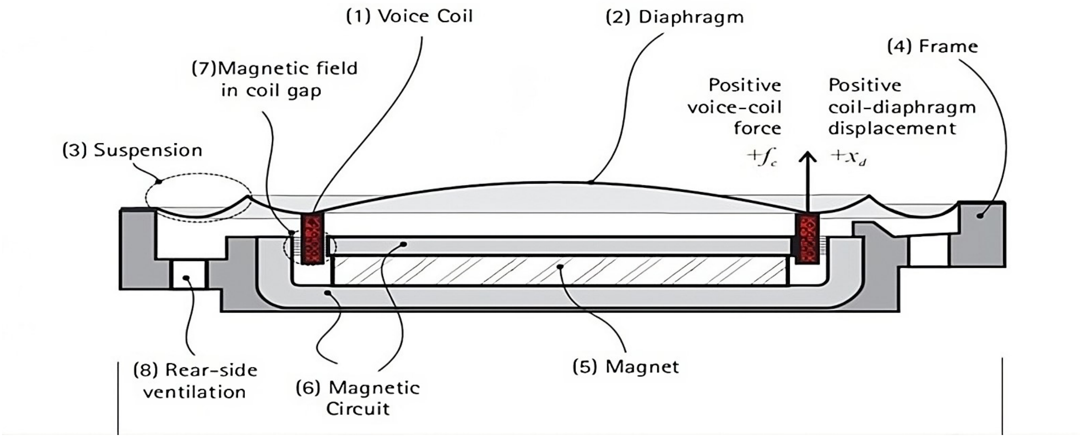
July 04, 2024

Table of Contents

Introduction

This document describes the aspects in theory used for designing micro-loudspeakers based on the moving coil principle. These elements will be realized as physical properties inside the loudspeaker as well as in the design of the acoustic environment around the loudspeaker for achieving a desired frequence response.

Fig. 1



A cross section of the moving coil loudspeaker.

The magnet system, the coil and the membrane can easily be seen as the active elements in the design, but also the acoustic elements present have a huge influence on the loudspeaker performance. These elements are harder to see on the cross section, but basically they are determined by the air flow inside the loudspeaker. E.g. the “air cushion” in front of the membrane is an acoustic element. Another acoustic element is the venting holes at the rear side of the speaker. A third acoustic element is the slit in the magnet system wherein the coil operates.

Acoustic elements and their values (impedance type analogy)

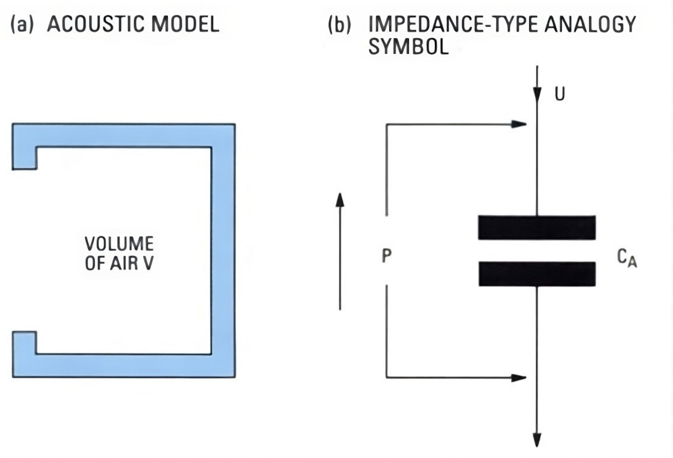
For a better understanding of these acoustic elements, the different types of acoustic elements will be explained here.

Acoustic Compliance

An airfilled volume acts as an acoustic spring. Sound pressure exerts a force on the air in the volume without displacing the confined air's center of gravity. This compression without acceleration is a characteristic of acoustic compliance.

In the presence of sound pressure, acoustic compliance behaves in a similar manner to an electrical capacitor in presence of an electric voltage as shown in *fig. 2*.

Fig. 2



The value of the acoustic compliance is directly proportional to the volume of confined air:

$Ca = V/(S0xc^2)$ $[m^5/N]$

Where:

V - *Volume*

S_0 - *air density (1.29 [kg/m³])*

c - *speed of sound (344 [m/s] at 22°C)*

In fig.2, *p* represents the sound pressure difference between the confined air and an open volume, while *U* is the volume velocity (product of the area of a surface element and the normal component of instantaneous particle velocity) for the acoustic element (in this case a compliance). Since all air volumes refer to a volume of infinite size (free field), all acoustic compliances converge to a common reference point (ground).

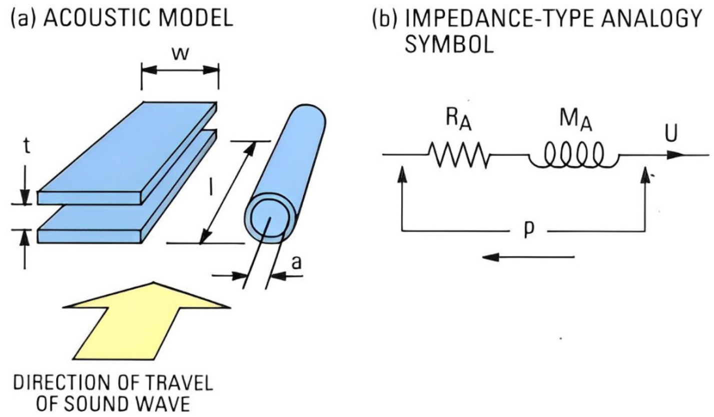
Acoustic Mass

The term acoustic “mass” describes an air mass, which accelerates under sound pressure without being compressed, as occurs in a slit or tube. When influenced by sound pressure, the slit or tube behaves like an inductance in series with a resistance when subjected to an electric voltage *(Fig.3)*.

Acoustic Loss

The last element to be considered is an acoustic loss. In part, this consists of friction loss which can be caused by relatively dense materials that has no tube effect, such as insulation, gauze or mesh. As there is no specific formula for calculating the acoustic loss of such materials, empirical methods must be used to determine the loss. The manufacturer of acoustic mesh or filter material very often specify the air flow through a wowen or nonwowen material and, in case of wowen material, also the size of the treads used as well as the distance between the treads. This information can be used to estimate the corresponding acoustic loss value.

Fig. 3



The series resistor takes account for acoustic loss caused by friction between the air and the walls inside the tube or slit.
Acoustic mass M_A and loss R_A for a slit where t[m] <0.003 $f^{-0.5}$ [m] are given by:

M_A = $(6*S_0*l)/(5wt)$ [kg/m^4]

R_A = $(12*l*r_o)/(t^3*w)$ [Ns/m^5]

Where:

l - depth of the slit
t - thickness of the slit
w - width of the slit
r_o - viscosity of air (1.86E-5 [Ns/m^5]
f - frequency

The acoustic parameters for tubes are given by several formulas depending on their radius. For a tube with a radius of up to $0.002xf^{-0.5}$, the values are:

M_A = $(4xS_0xl)/(3a^2xpii)$ [kg/m^4]

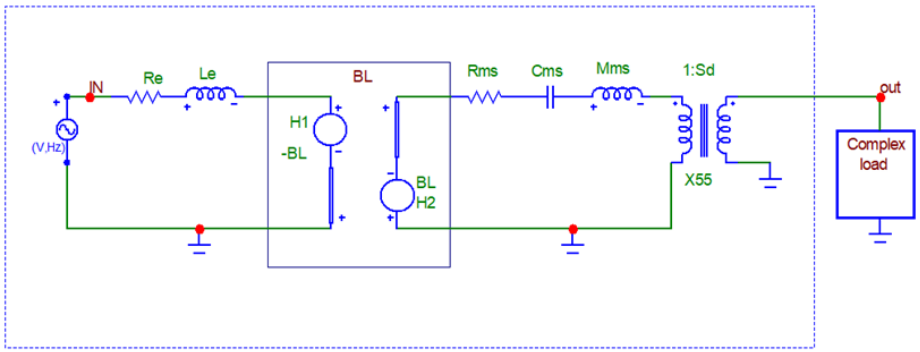
R_A = $(8xlxr_0)/(piia^4)$ [Ns/m^5]

For tubes with larger radii, the formulas are in part more complex than those previously mentioned and are not considered here.

Universal equivalent circuit for the moving coil loudspeaker

The simplest (universal) equivalent circuit for the moving coil loudspeaker is shown in *fig. 4* below:

Fig. 4



Electrical domain Mechanical domain Acoustical domain

As shown, this circuit is divided in electrical, mechanical, and acoustic networks which are mutually connected via transformers with ratios of **Bl :1** and **1:s**.

The first **(Bl:1)** is a **current-to-force** transformer, where **B** is the strenght of the magnetic field in which the coil operates and **l** is the length of the wire in the magnetic field. The second **(1:s)** is a **force-to-pressure** transformer, where **s** is the area of the active piston of the membrane, which produces the sound pressure.

The remaining key elements are:

Re	-	Electrical resistance of wire in the moving coil [ohm]
Le	-	Electrical inductance of the moving coil [H]
Mms	-	Moving mass of membrane (mass of piston plate + coil + moving part of suspension) [kg]
Cms	-	Compliance of suspension (hinge) [m/N]
Rms	-	Loss element of suspension (hinge) [m/Ns]
Complex load	-	Acoustic load of the diaphragm [m^5/Ns]
VHz	-	Electrical signal generator, which activates the terminals of the loudspeaker [V]

Development of a full detailed equivalent circuit for a micro loudspeaker

Though the physical dimensions inside a micro loudspeaker are very small, they all represents acoustic elements that influence the micro loudspeakers performance. Therefore, it is necessary to expand the universal equivalent circuit to include a more detailed representation that incorporates all acoustic elements.

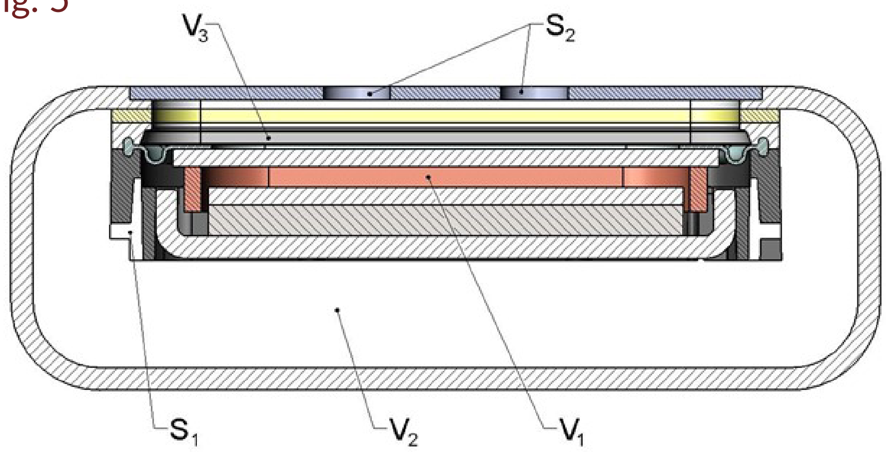
As an example, a typical 11x15mm loudspeaker is chosen.

The electrical and mechanical parameters for this loudspeaker are:

• Re: (Electrical resistance of coil wire)	7.6 [ohm]
• Le: (Electrical Inductance of coil)	6E-5 [H]
• Cms: (Mechanical Compliance of silicone suspension)[mm/N]	1.4E-3
• Mms: (Moving Mass (coil + piston plate)	8E-5 [kg]
• Rms: (Mechanical friction loss in suspension)	2.5E-1 [Ns/m]
• Bl: (Magnetic field strenght in air gab x length of wire)	0.88 [Tm]
• s: (Effective area of piston plate)	1.1E-4 [m2]

If we examine the cross-section of an 11x15mm loudspeaker integrated into a module with a back cavity of 1.5cm² *(see fig. 5)* and apply our understanding of acoustic elements, we can identify the following active acoustic elements in the 11x15mm loudspeaker module:

Fig. 5



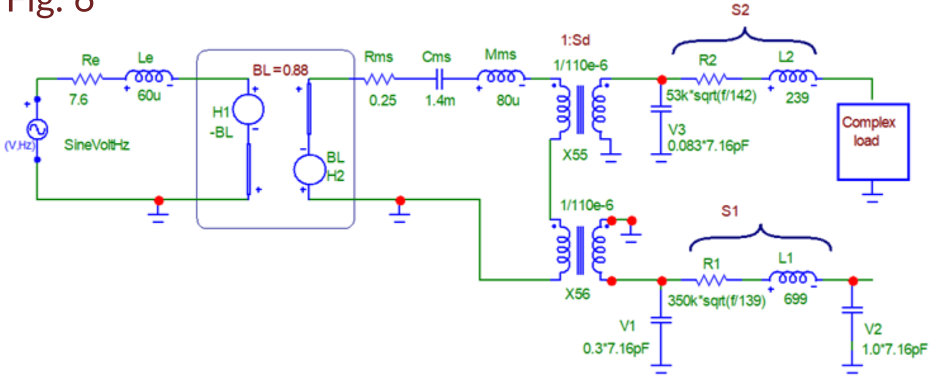
S represents slits, and **V** represents air volumes.

- V_1: (acoustic compliance of air volume on rear side of membrane)
- V_2: (acoustic compliance of air volume in back cavity)
- V_3: (acoustic compliance of air in front of membrane)
- S_1: (acoustic Mass of slit openings in corners of outer pole piece)
- S_2: (acoustic mass of sound outlet in module)

Drawing on our understanding of the properties of acoustic elements, slit or tube connections are equivalent to an acoustic resistance in series with an acoustic mass, while an air volume corresponds to an acoustic compliance.

This will lead to the complete equivalent diagram for the 11x15mm loudspeaker integrated into a module as shown in *fig. 6* below:

Fig. 6

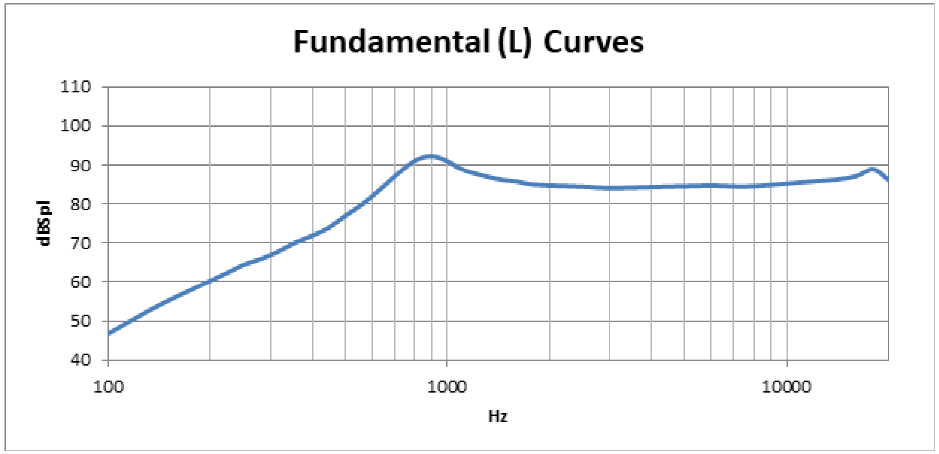


The acoustic complex load represents the radiation impedance of the free air that loads the sound pressure outside the sound outlet hole of the module. This load is inherently complex, and for simplicity, is represented here as a single component. More accurate models are available, but will not be discussed in this context.

The capacitors V1, V2 & V3 in *fig. 5* represents the three air volumes involved and S1 & S2 represents the two slit connections present in the design example.
For making the equivalent diagram more accurate, the diaphragm is split into two partial diaphragms, namely the area inside the coil attachment circumference as one area and the other area as being outside the circumference of the coil attachment.
Therefore, the equivalent diagram in figure 6 contains two separate force to pressure transformers.

With this complete equivalent diagram of the module, it becomes possible to simulate the linear performance using computer software. The frequency response simulation is illustrated in *fig. 7*.

Fig. 7



The resonance that can be seen at approx. 900Hz is the mechanical resonance (mech. mass and mech. compliance). This resonance, in combination with the acoustic compliance of the back cavity in the module (C2), occurs at this frequency. By changing the size of the back cavity, this resonance frequency can be changed up or down. Correspondingly the resonance frequency can also be changed by changing either the mass or the mechanical compliance (or both) of the moving system in the loudspeaker.

The resonance peak at approx. 18kHz is controlled by the stiffness of the membrane piston in conjunction with the acoustic mass of the sound outlet hole(s) in the module. The peak can be shifted to a lower frequency by reducing the size of the sound outlet hole(s) in the module. This could be the case when a certain balance between bass and treble is desired. However, where to place this balance between bass and treble can be very subjective. A common design goal is to maximize bandwidth by using the stiffest and lightest piston material for the membrane, enhancing high-frequency sound reproduction.

Conclusion

This White Paper *(WP03)* focuses on designing a micro loudspeaker with the expectation that all elements will behave in a linear and ideal manner. Unfortunately, this is not the case. When driving such small loudspeakers to deliver the highest possible sound pressure levels, several internal elements tend to shift from linear to nonlinear behavior. This shift results in unwanted contributions, such as harmonic distortion and Rub&Buzz (R&B), which degrade the sound quality.

A subsequent White Paper, *(WP04)*, titled "Designing Micro loudspeakers for Portable Devices Part II," will be released soon, addressing how to effectively mitigate these nonlinear issues.

In case of questions or a wish for a dialog, the following e-mail address and mobile phone number can be used:

Morten Kjeldsen, B.Sc.E.E.
Specialist, Micro Acoustics
Advanced Development, Ole Wolff A/S

e-mail: mk@owolff.com
Mobile: +45 26 32 28 79