Acoustic laboratories ♯8
Loudspeaker driver

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Goals: In this sessions, the students will characterize the reverberation chamber in the low-frequencies. Two phases wull be undertaken:

- a first simulation with COMSOL Multiphysics
- an experimental assessment in the frequency domain (using the Pulse Hardware)

Material

For the laboratory, you will use:

- COMSOL Multiphysics
- an anechoic room
- an Audax HT210F0 loudspeaker mounted on a screen
- a Bruel & Kjaer Type 2706 power amplifier
- a 1 Ω resistor
- a small mass + sticky gum
- 1 PCB microphone (Type 378B02)
- a Pulse Multichannel Sound and Vibration Analyzer
- a computer with the Pulse Software Suite

Part I
Loudspeaker driver modeling with COMSOL Mulitphysics

Open the COMSOL tutorial "models.aco.loudspeaker_driver.pdf" document and follow the instructions.

Part II
Loudspeaker measurements

1 Loudspeaker Thiele-Small parameters identification

In this part, you will identify the Thiele-Small parameters of a loudspeaker, namely:

Parameter	Symbol	Value	Unit
dc resistance	R_e	...	Ω
self inductance	L_e	...	H
resonance frequency	f_s	...	Hz
mechanical quality factor	Q_{ms}	...	-
electrical quality factor	Q_{es}	...	-
total quality factor	Q_{ts}	...	-
mechanical mass	M_{ms}	...	kg
mechanical compliance	C_{ms}	...	m.N^{-1}
mechanical resistance	R_{ms}	...	N.s.m^{-1}
force factor	$B\ell$	...	N/A
radiation area	S_d	...	m^2
equivalent air volume	V_{as}	...	m^3

Table 1: Definiton of the Thiele-Small parameters

The input impedance of a loudspeaker is then fully defined as:

$$Z_{hp} = R_e + j\omega L_e + \frac{(B\ell)^2}{j\omega M_{ms} + R_{ms} + \dfrac{1}{j\omega C_{ms}}} \tag{1}$$

In this exercise, we will consider mass M_{ms} already accounts for the radiation mass $2.M_{ar}$ of the piston (2 sides are radiating). The radiation resistance R_{ar} is neglected.

1.1 Setup

Connect the loudspeaker to the power amplifier and the test resistor as described on Figure 1. It is advised to install the loudspeaker, as well as the power amplifier and test resistor inside the anechoic chamber, while the Pulse analyzer is installed in the laboratory.
First, you will measure the input electrical impedance with the proposed setup. For this, you need to set the FFT analyzer so that it estimates H_1 transfer functions between input voltage U_{ls} and current I_{ls}.

1.2 Identification of R_e and L_e

The first measurement consists in assessing the dc resistance R_e and the self-inductance L_e of the loudspeaker. The first quantity can be easily estimated with a simple ohm-meter connected to the electrical input of the loudspeaker.

Question:
Estimate R_e with the ohm-meter.

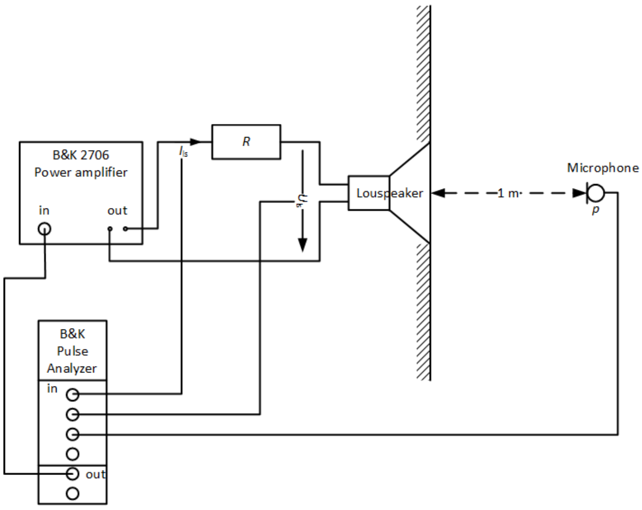

Figure 1: Experimental setup

Now, we will estimate the self-inductance L_e, that shall manifest in the high-frequency range (according to Eq. (1)).

You will do a first test measurement of the input electrical impedance $\hat{Z}_{ls} = \dfrac{U_{ls}}{I_{ls}}$ over the full-band [**20** - 20'000 Hz] (to avoid delivering a dc component to the loudspeaker, that might harm it). First set the FFT Analyzer to process over the frequency-band of interest with the finer possible frequency resolution.

Then set the signal Generator to deliver a **bidirectional, logarithmic** swept-sine over the same frequency range. Set the sweep rate to 0.2 decades/second.

Important note: For security reasons, first set the amplitude of the generator to a low value (eg. 10 mV), and set the power amplifier to a low gain (eg. 1). Measure the rms voltage at the input of the loudspeaker, and modify the signal amplitude (either on the signal generator or the power amplifier) in order to achieve $U_{ls} \approx 100$ mV. Do not change this value during the whole exercise.

Question:
What is the total time required to scan the whole frequency band [20 - 20'000 Hz]? Set the FFT Analyzer averaging to "Linear" and set the averaging time to perform FFT Analyses during a single bidirectional sequence [20 Hz - 20 kHz - 20 Hz]

Once set up, launch a measurement of the input electric impedance $\hat{Z}_{ls} = \dfrac{U_{ls}}{I_{ls}}$. You should have a curve like the one in Figure 2.

Question:
Check the dc resistance R_e value, and estimate the self-inductance L_e by linear regression at high frequencies. It is advised to zoom on the high-frequency asymptotic behaviour (then change the FFT Analyzer and Generator settings accordingly).

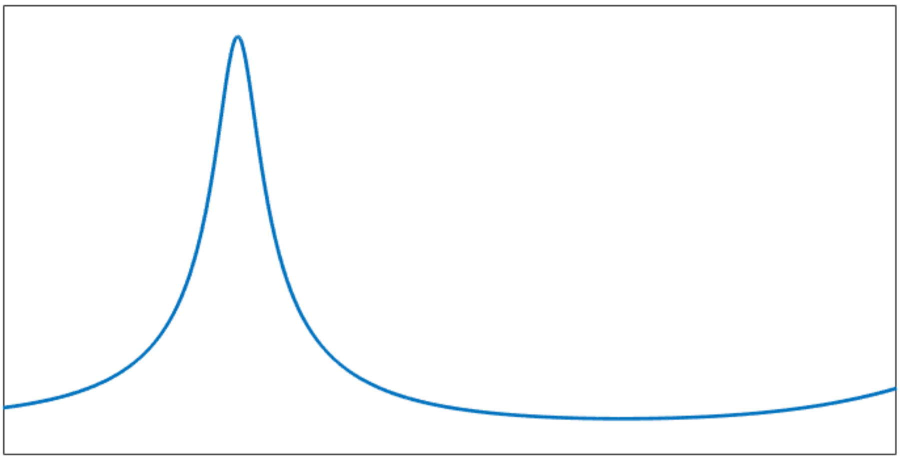

Figure 2: Measured $|Z_{hp}(f)|$

1.3 Identification of resonance frequency f_s

Now we will zoom around the bump in the low-mid frequency range. Modify the FFT analyzer and Generator settings to focus measurements on **one frequency decade** around the central frequency of the bump.

From now on, you will compute $z_{hp} = \frac{Z_{hp}}{R_e}$.

Question: Draw the normalized electric impedance magnitude $|z_{hp}|$.

The resonance frequency f_s corresponds to the argument of $\max(|z_{hp}|)$. To identify f_s with the best accuracy, we will first measure $r_0 = \max(|z_{hp}|)$.

Question:

What is the value of r_0?

Let's define $r_1 = \sqrt{r_0}$.

Question:

Find frequencies f_1 and f_2 for which $|z_{hp}(f_{1,2})| = r_1$.

Demonstrate that $f_s = \sqrt{f_1, f_2}$ (hint: start with the definition of Eq. (1)).

Evaluate f_s based on f_1 and f_2.

1.4 Identification of the mechanical quality factor Q_{ms}

The mechanical quality factor accounts for the only mechanical losses associated with the mechanical resonance, namely: $Q_{ms} = \frac{1}{R_{ms}}\sqrt{\frac{M_{ms}}{C_{ms}}}$. However, R_{ms}, M_{ms}, C_{ms} are unknwon for the time being...

Nevertheless, it is directly linked to the electrical impedance resonance, by computing $Q_{ms} = \sqrt{r_0}\frac{f_s}{f_2 - f_1}$ (you are not asked to prove this...).

Question:

the mechanical quality factor of the loudspeaker Q_{ms}.

1.5 Identification of the electrical quality factor Q_{es}

In the same way, the electrical quality factor accounts for the only electrical losses associated with the mechanical resonance, namely: $Q_{es} = \dfrac{R_e}{(B\ell)^2}\sqrt{\dfrac{M_{ms}}{C_{ms}}}$. It can also be deduced from the resonance as $Q_{es} = \dfrac{Q_{ms}}{r_0 - 1} = \dfrac{\sqrt{r_0}}{r_0 - 1}\dfrac{f_s}{f_2 - f_1}$.

Question:

Evaluate the electrical quality factor of the loudspeaker Q_{es}.

1.6 Identification of total resonance quality factor Q_{ts}

The total quality factor Q_{ts} is defined as the quality factor accounting for both electrical and mechanical losses. It reads: $Q_{ts} = \dfrac{Q_{ms}Q_{es}}{Q_{ms} + Q_{es}}$.

Question:

Show that $Q_{ts} = \dfrac{1}{\sqrt{r_0}}\dfrac{f_s}{f_2 - f_1}$.

Evaluate Q_{ts}.

1.7 Identification of the moving mass M_{ms}

For the identification of the moving mass, we need to perform another measurement, where an additional mass is glued on the loudspeaker membrane. For that, you will need to take a small amount of lead pellets with the sticky gum to attach on the loudspeaker membrane. Please note that the additional weight should be of at least 20 g to allow a significant effect on the resonance frequency. Weigh the mass and note the value as m_{add}.

Once the mass is firmly glued on the loudspeaker membrane (try to avoid gluing on the central dust cap), repeat the preceding measurement.

Question:

Comment the new electric impedance curve. Compared to the former measurement, what is the effect of the attached mass? Can you explain this by using Eq. (1)?

Using the same procedure as before, estimate the new resonance frequency f'_s with the added mass m_{add}.

Show that $\left(\dfrac{f_s}{f'_s}\right)^2 = 1 + \dfrac{m_{add}}{M_{ms}}$.

Evaluate the moving mass value M_{ms}.

1.8 Identification of the mechanical compliance C_{ms}

You are now able to deduce the mechanical compliance with the preceding 2 experiments.

Question:

Give the expression and evaluate C_{ms}.

1.9 Identification of the mechanical resistance R_{ms}

Question:

Find a way to evaluate R_{ms} thanks to the above-mentioned parameters.

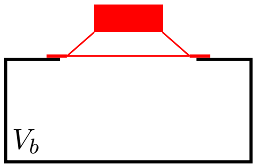

Figure 3: Closed-box mounting

1.10 Identification of force factor $B\ell$

Question:
Find a way to evaluate $B\ell$ thanks to an electric impedance measurement.

1.11 Estimation of the remaining parameters (S_d and V_{as})

In the remaining electrical measurements, the loudspeaker should be unmounted from the baffle and installed on a closed box instead, as described in Fig.3. We denote V_b the volume of the cabinet. We remind that, at low frequencies, a closed volume behaves as an acoustic compliance $C_{ab} = \dfrac{V_b}{\rho c^2}$.
Question:
Measure the electrical impedance of the loudspeaker mounted on the enclosure.
Comment the new impedance curve, and evaluate the new resonance frequency f_c.
Draw the acoustic scheme of the closed-box loudspeaker.
Show that the new resonance frequency reads: $f_c = \sqrt{1 + \dfrac{C_{ms}\, S_d^2}{C_{ab}}} f_s$, where S_d is the effective piston area.
Determine S_d.
Determine the equivalent air volume having the same acoustic compliance than C_{ms}: $V_{as} = \rho c^2 S_d^2 C_{ms}$.

2 Loudspeaker sensitivity (sound pressure under free-field)

2.1 Measurement

Now you will measure the pressure response of the loudspeaker, following the recommendations of IEC-60268-5 standard. The setup is the same as in Fig. 1 except the test resistor R that should be discarded.
Question:
Measure the sound pressure level of the loudspeaker under the test conditions specified in IEC-60268-5 standard. It should have the shape of Fig. 4.

2.2 Comparison with the lumped-element model

Atw-frequencies (for $ka << 1$, discarding the effect of the self-inductance) a loudspeaker mounted on a screen can be modelled with the following equivalent acoustic scheme, accounting for all electrical (blue), mechanical (red) and acoustical components in one single (acoustic) circuit, drawn on Fig.5.
The equivalent acoustic elements are defined in Table 2.
Moreover, we know that the radiated power (on one face, eg. face 1) is defined as $\mathcal{P}_a = R_{ar1} q_s^2$, and that the sound intensity at distance r in the far field of a piston on screen is defined as $I(r) = \dfrac{p(r)^2}{\rho c} = \dfrac{\mathcal{P}_a}{2\pi r^2}$.
Question:
Now that the whole Thiele-Small parameters are known, derive the transfer function between the

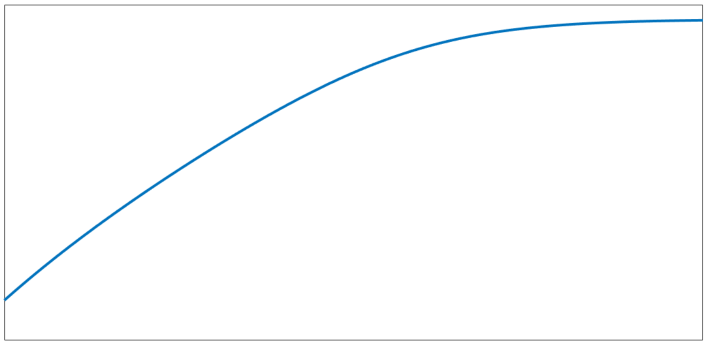

Figure 4: Measured SPL vs. frequency

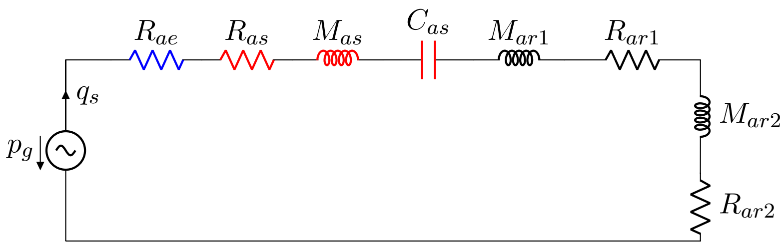

Figure 5: Equivalent acoustic circuit

radiated sound pressure (at a given distance) and the input voltage $\frac{p(r)}{U_g}$.
Compare the actual measurements and the theoretical curve in the prescribed test conditions.

Element	Electrical parameters	Mechanical parameters	Acoustical parameters
Voltage source	$p_g = \frac{B\ell}{S_d R_e} U_g$		
Resistance	$R_{ae} = (\frac{B\ell}{S_d})^2 \frac{1}{R_e}$	$R_{as} = \frac{R_{ms}}{S_d^2}$	$R_{ar1} = R_{ar2} = \frac{\rho c}{S_d} \frac{(ka)^2}{2}$
Inductance		$M_{as} = \frac{M_{ms}}{S_d^2}$	$M_{ar1} = M_{ar2} = \frac{8}{3\pi} \frac{\rho a}{S_d}$
Capacitance		$C_{as} = C_{ms} S_d^2$	

Table 2: Equivalent acoustic elements