Linear Simulation (LSIM) S58

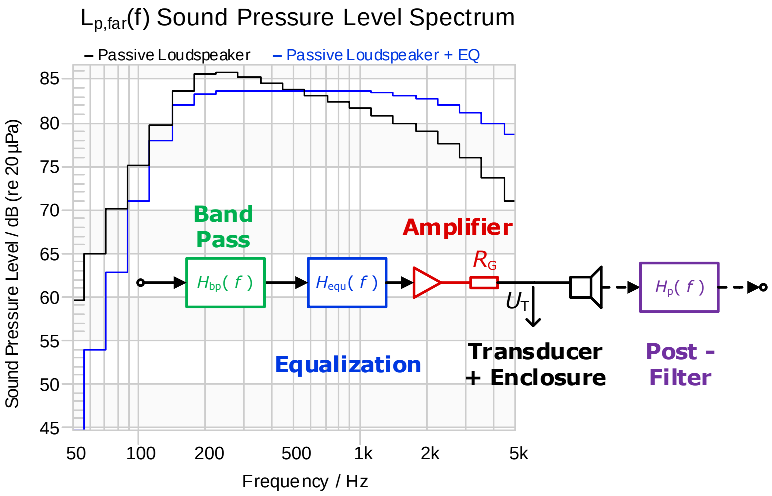
Module of the KLIPPEL ANALYZER SYSTEM (Document Revision 1.6)

FEATURES

- Linear signal modeling from digital input to acoustical output.
- Lumped network parameters for passive components
- Automatic equalization (DSP)
- Small signal performance for any audio input (music, test signal)
- Efficiency and voltage sensitivity versus frequency and broadband signals

BENEFITS

- Small signal performance in target application
- Considers digital, electrical, mechanical, acoustical components
- Minimum set of essential parameters
- Fast calculation of frequency responses
- Filter parameters for optimal system alignment
- Basis for large signal modeling (SIM)



DESCRIPTION

The *LSIM Linear Simulation* describes an active loudspeaker or headphone driver by using a linear lumped parameter model. Main components are equalizer, amplifier, transducer and enclosure. Using any selected input spectrum (e.g. music), meaningful statistical single values (e.g. mean efficiency) and various state spectra (e.g. SPL) are calculated. This is a useful base for defining transducer and amplifier requirements and providing significant information about the audio performance. Various transfer functions reveal the relationship between digital, electrical, mechanical and acoustical signals.

The *LSIM* features an easy-to-use simulation software with lumped or geometrical input parameters for initial (small signal) design, which is the basis for the large signal simulation in other Klippel software modules (*SIM Simulation*, *SIM-AUR Auralization*).

Article number	1000-300

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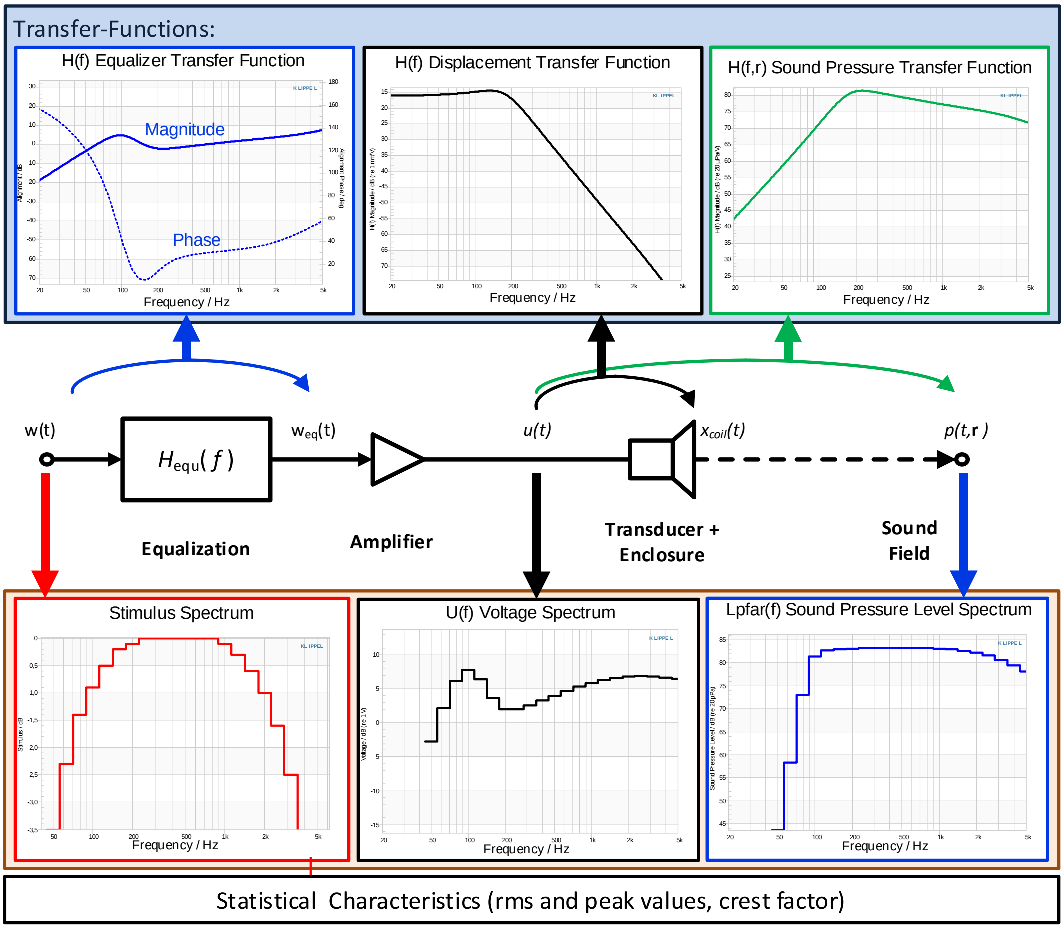
1 Overview

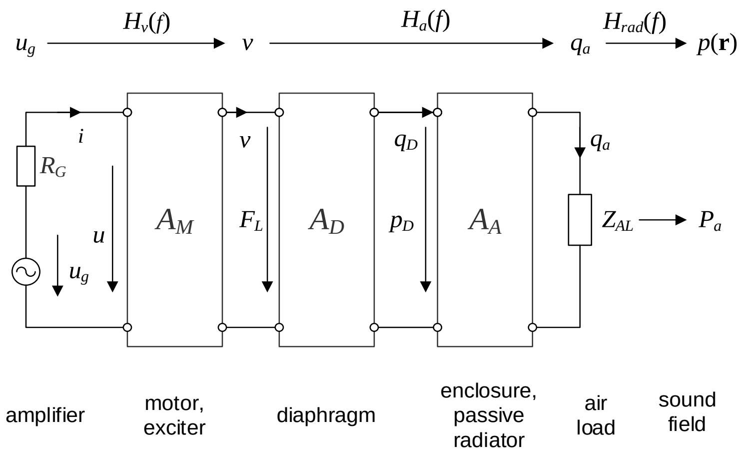
1.1 Principle

Basic Principle

The *LSIM Linear Simulation* module illustrates a simplified linear active loudspeaker containing a band pass filter section for simulating a crossover, a prefilter (Equalization) specified by the transfer function $H_{\mathrm{equ}}(f)$, an amplifier with an output resistance of R_{g} and an electrodynamical transducer mounted in an enclosure. The optimal equalizer transfer function $H_{\mathrm{equ}}(f)$ for system alignment will be calculated automatically for a specified target transfer behaviour.
Signal based system design is possible by defining a relative input spectrum $G_w(f)$. Pink noise, typical program material according to *IEC 60268-21* and an option for individual external stimulus are provided. All spectra are converted into third octave spaced spectra. Based on this, state variables like U_g(amplifier output voltage without load) or U_{T} (terminal voltage) and further characteristics like SPL_{max} can be predicted. Entering a crest factor provides the option to estimate peak values.



Lumped Parameter Model



The *LSIM Linear Simulation* module uses a lumped-parameter model of an electro-dynamical transducer mounted in common enclosures. This model is based on chain matrices describing the different parts of the loudspeaker. A_M describes the motor and mechanical behavior of the exciter, the diaphragm A_D, the enclosure A_A and passive acoustical elements like port or passive radiator. Employing this knowledge, total sound pressure level *SPL(f)*, state variables (e.g. V_c), transfer functions such as $H_x(f)$ or the electrical impedance $Z_{\mathrm{el}}(f)$, as well as efficiency $\eta(f)$ and voltage sensitivity can be easily simulated.
Note that the *LSIM* module only simulates the linear behavior of the system, which is considered valid at small amplitudes. Please see *SIM Simulation* or *SIM-AUR Simulation / Auralization* for nonlinear modeling.

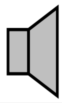
1.2 Input

Input Parameters

The LSIM input is structured into 4 categories:

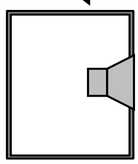
Transducer:

- Linear transducer parameters (free air)



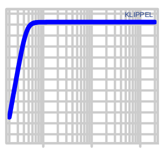
Enclosure:

- Type
- Geometrical properties or lumped parameters



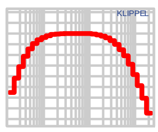
Equalization:

- High pass filter alignment
- User defined transfer behavior

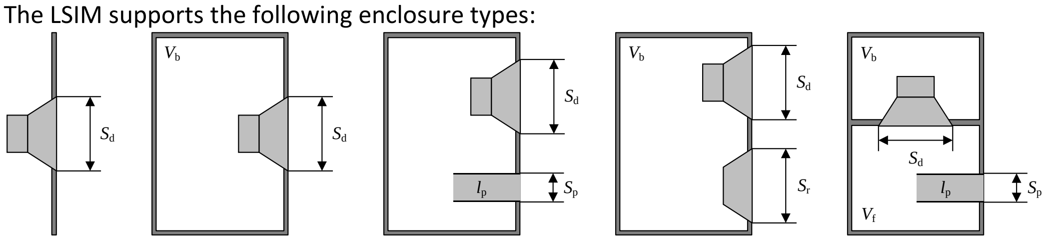


Stimulus:

- Pink noise
- Typical program material according to IEC 60268-21
- User defined spectrum (e.g. music)



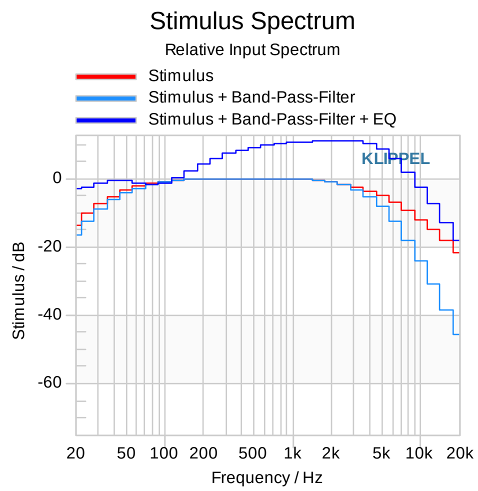
The LSIM supports the following enclosure types:

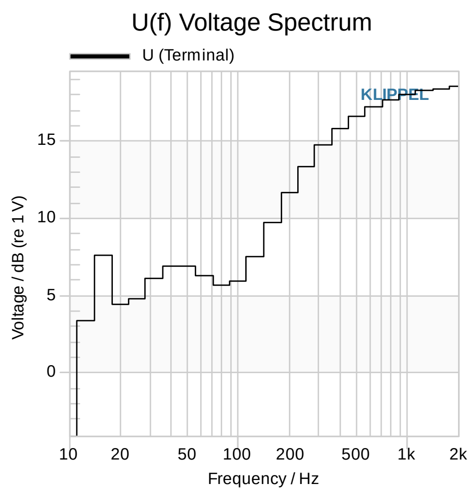


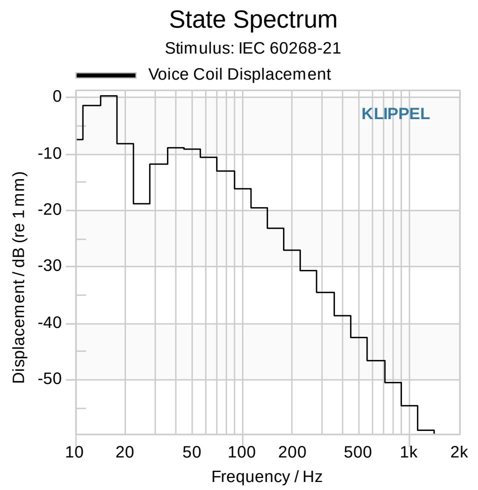
Baffle | Closed Box | Vented Box | Passive Radiator Box | Bandpass System

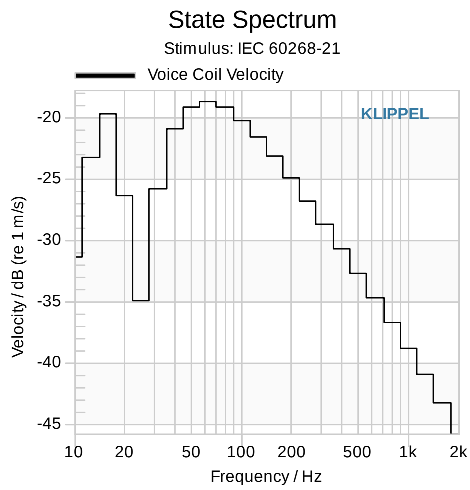
1.3 Results

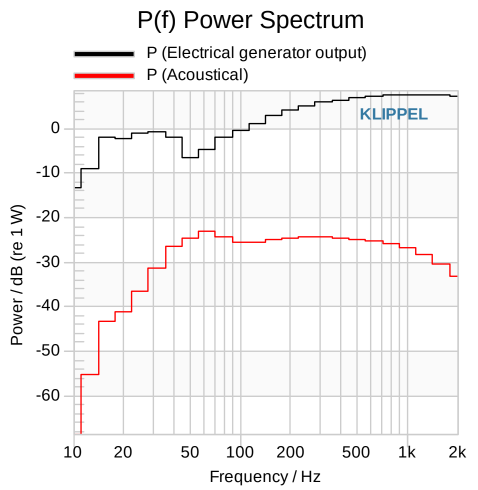
Linear Transfer Functions	The magnitude and phase frequency responses are calculated between the following state variables • Sound pressure level $L_{\mathrm{p}}(f,\boldsymbol{r})$ in far field • Displacement (voice coil, passive radiator) • Velocities (voice coil, passive radiator) • Forces in the mechanical system • Volume velocities in the acoustical system in relation to the terminal voltage U_{T}. The electrical input impedance $Z_{\mathrm{e}}(f)$ is also presented.
Reference Sensitivity	• Voltage sensitivity $L(f,\mathbf{r})$ versus frequency of a sinusoidal stimulus referenced to $u_{\mathrm{ref}} = 1\ \mathrm{V}$ and $r_{\mathrm{ref}} = 1\mathrm{m}$. • Reference voltage sensitivity L_{r} for the given broadband stimulus in accordance to IEC 60268-22.
Efficiency	• Efficiency $\eta(f)$ versus frequency of a sinusoidal stimulus. • Reference efficiency η_{r} for given broadband stimulus in accordance to IEC 60268-22.
Spectra based on Stimulus	For a given broadband stimulus spectrum, the following 1/3rd octave spectra are available: • Stimulus (with no filter, band-pass filtered, or band-pass and equalized) • Internal state variables (e.g. Displacement for given stimulus) • Power (electrical input, acoustical output)

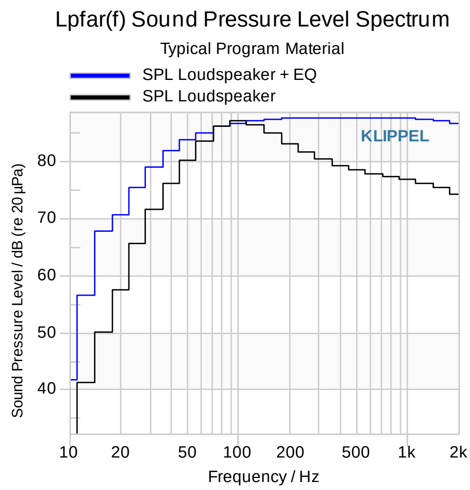












Single values

Characteristics depending on the broadband stimulus:

- $L_{\mathrm{p}}(\mathrm{r})$ Total SPL at an evaluation point r in far field
- $U_{\mathrm{T(rms)}}; U_{\mathrm{T(peak)}}$ Terminal voltage
- $I_{\mathrm{T(rms)}}; I_{\mathrm{T(peak)}}$ Input current at the loudspeaker terminal
- $X_{\mathrm{C(rms)}}; X_{C(\mathrm{peak})}$ Voice coil displacement
- $V_{C(rms)}$ Voice coil velocity
- η_{R} Reference voltage sensitivity
- L_{R} Reference efficiency
- P_{e} Total electrical transducer input power
- P_{a} Total acoustical output power

2 Example

2.1 Simulation of a closed box system

Targets

The target of this example is to show a typical workflow on how to use the *LSIM* for active loudspeaker design. The task is to use the *LSIM* for designing a two-way closed box loudspeaker. We define the following design targets:

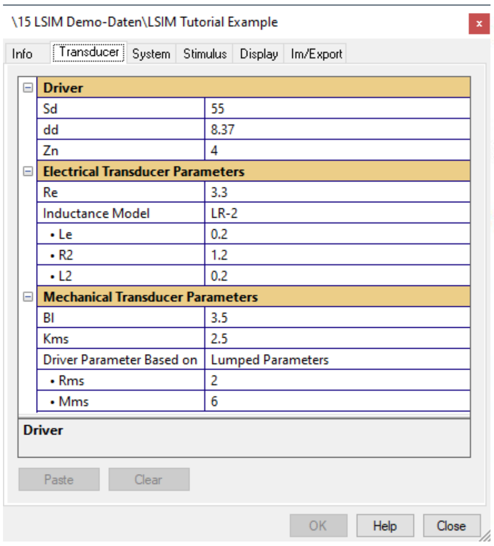
- The desired SPL output is 95 dB in 1 m distance in half-room.
- The volume of the box is limited to 1 l due to design choices.
- A 4” transducer with a maximum specified displacement of x_{max} = 5 mm shall be used.
- Crossover frequency to the tweeter f_{xo}=5 kHz

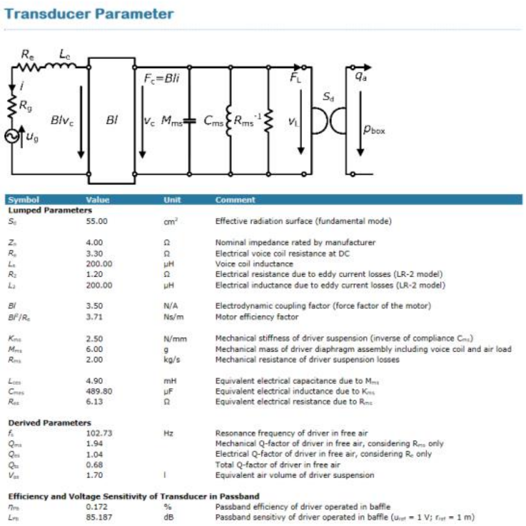
The following critical single values should be determined for typical program material with respect to these design targets:

- Power and voltage consumption (required for selecting a fitting amplifier)
- Efficiency and Voltage Sensitivity
- Peak voice coil displacement

Parameters

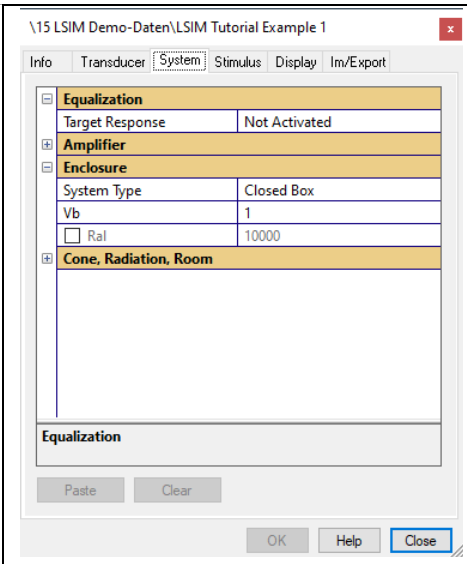
1. Linear Transducer Parameters: Data of a small midrange speaker was imported from an LPM operation.

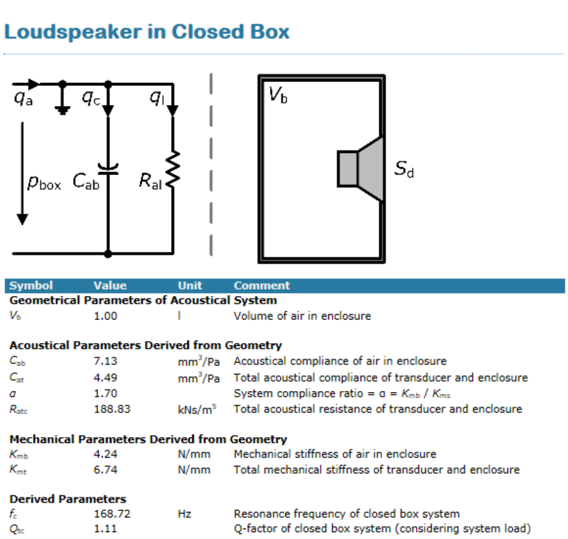




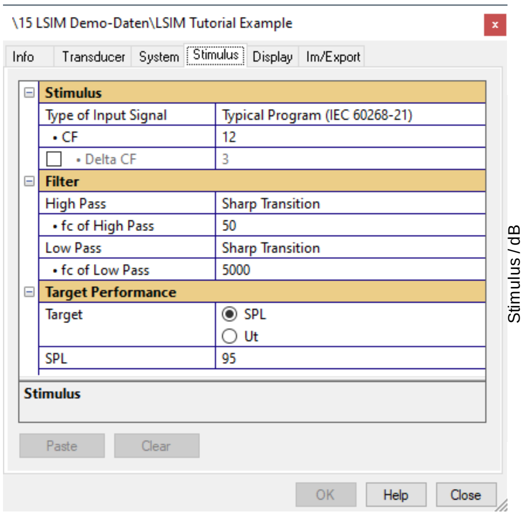
Symbol	Value	Unit	Comment
Lumped Parameters			
S_d	55.00	cm²	Effective radiation surface (fundamental mode)
Z_n	4.00	Ω	Nominal impedance rated by manufacturer
R_e	3.30	Ω	Electrical voice coil resistance at DC
L_e	200.00	µH	Voice coil inductance
R_2	1.20	Ω	Electrical resistance due to eddy current losses (LR-2 model)
L_2	200.00	µH	Electrical inductance due to eddy current losses (LR-2 model)
Bl	3.50	N/A	Electrodynamic coupling factor (force factor of the motor)
Bl^2/R_e	3.71	Ns/m	Motor efficiency factor
K_{ms}	2.50	N/mm	Mechanical stiffness of driver suspension (inverse of compliance C_{ms})
M_{ms}	6.00	g	Mechanical mass of driver diaphragm assembly including voice coil and air load
R_{ms}	2.00	kg/s	Mechanical resistance of driver suspension losses
L_{ces}	4.90	mH	Equivalent electrical capacitance due to M_{ms}
C_{mes}	489.80	µF	Equivalent electrical inductance due to K_{ms}
R_{es}	6.13	Ω	Equivalent electrical resistance due to R_{ms}
Derived Parameters			
f_s	102.73	Hz	Resonance frequency of driver in free air
Q_{ms}	1.94		Mechanical Q-factor of driver in free air, considering R_{ms} only
Q_{es}	1.04		Electrical Q-factor of driver in free air, considering R_e only
Q_{ts}	0.68		Total Q-factor of driver in free air
V_{as}	1.70	l	Equivalent air volume of driver suspension
Efficiency and Voltage Sensitivity of Transducer in Passband			
η_{ms}	0.172	%	Passband efficiency of driver operated in baffle
L_m	85.187	dB	Passband sensitivy of driver operated in baffle (u_{ref} = 1 V; r_{ref} = 1 m)

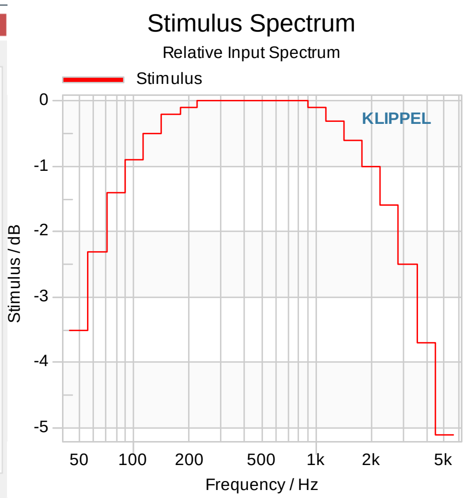
2. System parameters: The closed box loudspeaker is specified with a volume of 1 l. In the first step no equalization is applied to the system.
   For simplification, no amplifier output resistance Rg, leakage losses Ral and post-filter is selected. The window Table System Parameters shows the headline Loudspeaker in Closed Box indicating the selected enclosure system. The picture below shows the corresponding equivalent circuit. The table below contains all derived enclosure parameters based on the entered closed-box parameters.





3. Stimulus Parameters: The stimulus that is used for calculating transducer and system states is specified on the property page's category Stimulus. The spectrum defined in IEC 60268-21 is a good representation of common broadband music stimuli and very well suited for the simulation. A typical crest factor is 12 dB. For the specified small speaker, a frequency-band from 50 Hz (SPL output is negligible below) to 5 kHz (crossover frequency) is of interest. The desired 95 dB is entered for Target SPL.
   The window stimulus spectrum shows the relative stimulus spectrum.





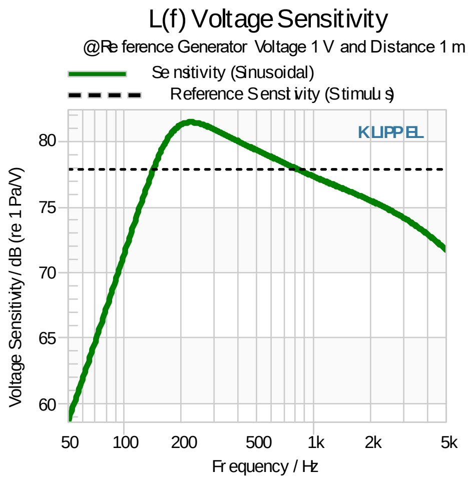
Results

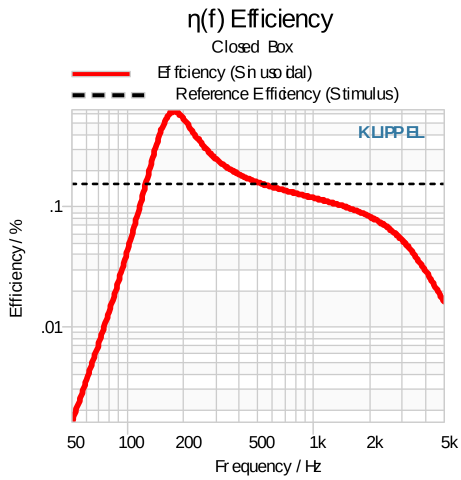
The single values listed in table *State Variables* provide the most important information considering the simulated music reproduction:

1. For generating 95 dB SPL output using the desired IEC signal, the amplifier has to provide about 11 W. The peak voltage for an estimated crest factor of 12 is approx. 28 V.
2. The resulting effective (*reference*) efficiency is approx. 0.16 % for the selected stimulus. The effective (*reference*) voltage sensitivity is 78 dB.
3. For the specified stimulus, a peak displacement of approx. 2.86 mm is expected.

These values are the basis for defining the amplifier and transducer requirements. Checking the limits defined in the task above reveals that the desired SPL is achievable without exceeding the transducer's maximum displacement.

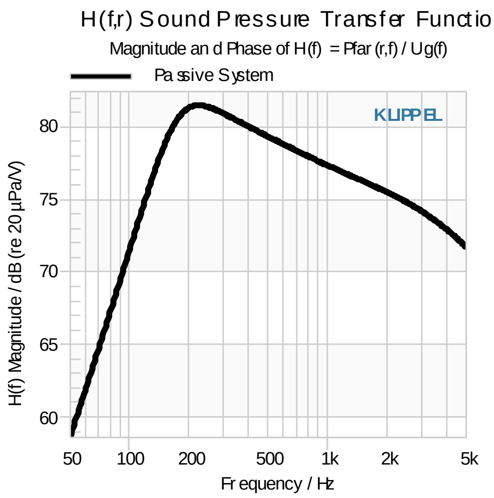
Viewing the curves *efficiency and voltage sensitivity versus frequency* is useful to understand the limitations of the passive loudspeaker system. The efficiency at lower frequencies decreases rapidly, so pushing frequencies to very low frequencies will be inefficient. Pay attention: Efficiency and voltage-sensitivity are not equal. Efficiency shows the ratio between incoming and outgoing power in percent. Voltage sensitivity shows the SPL output at 1 m distance with a terminal voltage of 1 V.

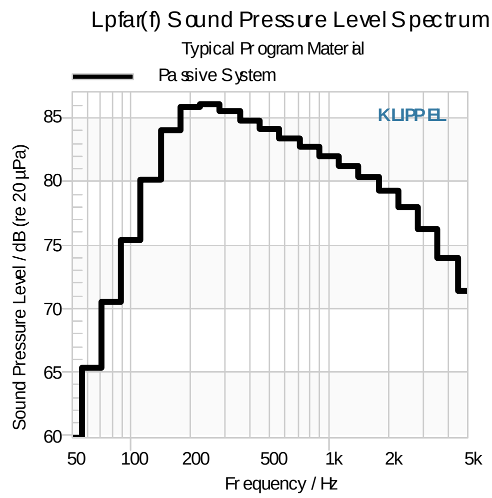




Adding Equalization

As the sound pressure transfer function (see chart below) shows, the frequency response is not equalized and the cutoff frequency is very high (~170 Hz).



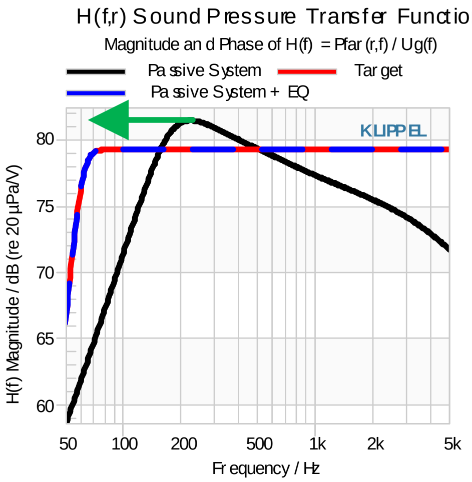


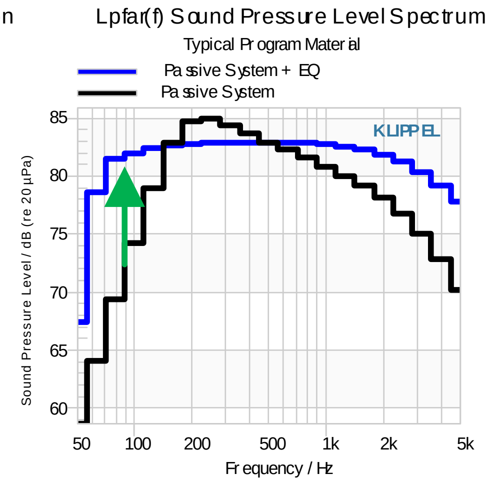
This section explains how to reduce the active system's cut-off frequency and how to apply equalization at higher frequencies.

Finding a good compromise for the optimal target high-pass characteristic is crucial for optimum performance: Setting the cut-off frequency too low will result in an inefficient system prone to extreme voltage requirements. Setting the cut-off frequency too high leads to a lack of bass and wasted potential. For the first simulation we define the following target response:

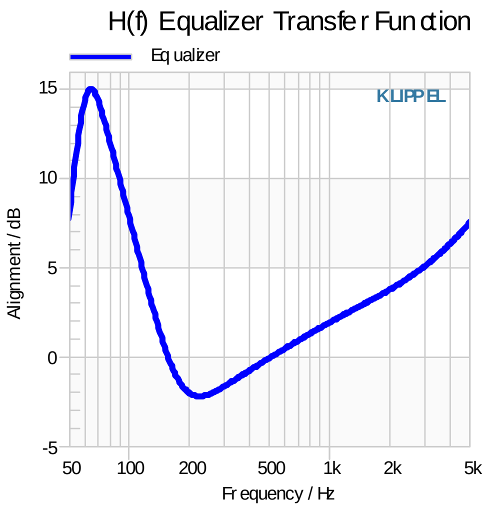
- Cut-off frequency: 60 Hz
- Filter type: 6^{th} order Chebyshev filter

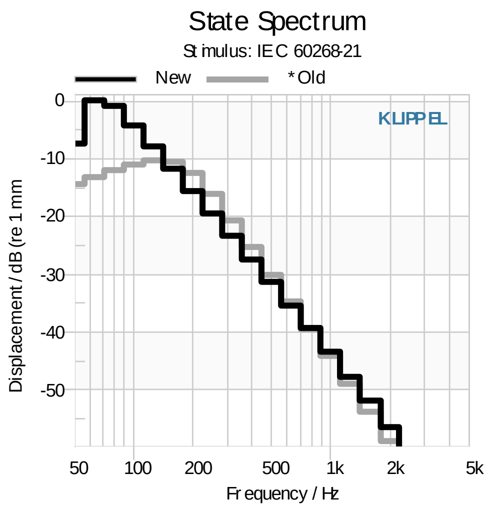
A 6^{th} order filter is used to avoid wasting voltage and displacement below the cut-off frequency where the voltage sensitivity drops significantly (Compare *H(f,r) Sound Pressure* and *H(f) Displacement*). See the sound pressure transfer function and spectrum which shows the impact of the alignment filter on the sound pressure.





Applying this alignment filter results in a peak voltage of approx. 47 V and an electrical power of almost 34 W to achieve the desired 95 dB SPL output. The required peak displacement is 6.6 mm now. These values have increased dramatically compared to the passive system. This is caused by the excessive bass boost defined by the target alignment. As can be seen in the chart below, the alignment is boosting low frequencies up to 15 dB. In the *State Variables* window, the effective voltage boost L_{EQ} for the selected stimulus is displayed (in this case the boost is 5.5 dB).





As the estimated displacement exceeds the transducer specification and the electrical power will heat up the voice coil too much (typical thermal resistance of this transducer type is 3…5 K/W) reducing efficiency, the initially used cut-off frequency should be increased.
For the next simulation we use the following target alignment:

- Cut-off frequency: 75 Hz
- Filter type: 6th order Chebyshev filter

Now the peak voice coil displacement is below the limit ($x_{c,peak}$ = 4.7 mm), the electrical power for this stimulus is 20 W and the peak voltage is 38 V. If the amplifier can deliver this voltage, the chosen target alignment is reasonable. If a weaker amplifier is used, the cut-off frequency has to be increased or the design targets to be relaxed.
Comparing the reference efficiency and reference voltage sensitivity between the passive system and the equalized system reveals that the bass enhancement results in a speaker with linear frequency response and much better low frequency response at the cost of lower efficiency:

- $L_{R,\,old}$ = 77.9 dB; $\eta_{R,\,old}$ = 0.16 %;

	- $L_{R, new}$ = 75.4 dB; $\eta_{R, new}$ = 0.09 %;

3 Requirements

3.1 Hardware

License Device	*Klippel Dongle* or *Klippel Analyzer 3* may be used to run this product.

3.2 Software

dB-Lab (>210.560)	dB-Lab is the project management software of the KLIPPEL R&D SYSTEM.

4 Parameter

4.1 Input

4.1.1 Electro Dynamic Transducer

Parameter	Symbol	Unit
Effective radiation surface	S_d	cm^2
Diameter of round effective radiation surface	d_d	cm
Nominal impedance rated by manufacturer	Z_n	Ω
Electrical voice-coil resistance at DC	R_e	Ω
Voice coil inductance	L_e	mH
Electric resistance due to eddy current losses	R_2	Ω
Electrical inductance due to eddy current losses	L_2	mH
Electric resistance due to eddy current losses	R_3	Ω
Electrical inductance due to eddy current losses	L_3	mH
Factor in LEACH model	K	Ω
Exponent in LEACH model	n	---
Factor of real part in WRIGHT model	K_{rm}	Ω
Exponent of real part in WRIGHT model	E_{rm}	---
Factor of imaginary part in WRIGHT model	K_{xm}	Ω
Exponent of imaginary part in WRIGHT model	E_{xm}	---
Effective instantaneous electrodynamic coupling factor (force factor of the motor) defined by the integral of the magnetic flux density B over the voice coil length l	Bl	N/A
Mechanical stiffness of driver suspension (inverse of compliance C_{ms})	K_{ms}	N/mm
Mechanical resistance of driver suspension losses	R_{ms}	kg/s
Mechanical mass of driver diaphragm assembly including voice coil and air load	M_{ms}	g
Transducer resonance frequency (influences Rms and M_{ms})	f_s	Hz
Mechanical Q-factor of driver in free air, considering R_{ms} only (influences R_{ms})	Q_{ts}	---

4.1.2 Equalization

High pass filter alignment:

Alignment Type:
1. Biquad filter
2. Bessel filter (4th and 6th order)
3. Chebyshev filter (4th and 6th order)
4. Butterworth filter (4th and 6th order)

Parameter	Symbol	Unit
Target Cutoff Frequency	f_0	Hz

Chebyshev Constant	$C_{\mathrm{Chebyshev}}$	---
Arbitrary target transfer behavior		
Target response as matrix containing frequencies and corresponding levels		

4.1.3 Amplifier

Parameter	Symbol	Unit
Output-resistance of amplifier output including cables	R_{g}	Ω

4.1.4 Stimulus

Type of input signal:
1. Pink noise
2. Typical program (IEC 60268-21)
3. External spectrum

Bandpass:
1. Ideal (rectangle)
2. Butterworth

Parameter	Symbol	Unit
Cutoff frequency of the high pass filter	f_{cHP}	Hz
Slope of high pass filter	m_{HP}	dB
Cutoff frequency of the Low pass filter	f_{cLP}	Hz
Slope of low pass filter	m_{LP}	dB
Crest factor	CF	dB
Difference between crest factor for voltage and current signal and crest factor for displacement signal	ΔCF	dB

4.1.5 Enclosure

Enclosure type:
1. Baffle
2. Closed box
3. Vented box (with slit or tube-shaped vent)
4. Box with passive radiator
5. Bandpass system (with slit or tube-shaped vent)

Parameter	Symbol	Unit
Geometrical parameters:		
Volume of air in enclosure	V_{b}	l
Surface area of port	S_{p}	cm^2
Diameter of port	d_{p}	cm
Length of port	l_{p}	cm
Width of surface area of port	w_{p}	cm
Height of surface area of port	h_{p}	cm
Effective projected surface area of passive radiator diaphragm	S_{r}	cm^2
Diameter of round effective projected surface area of passive radiator diaphragm	d_{r}	cm
Volume of air in front enclosure	V_{f}	l
Lumped parameters:		
Acoustic resistance of losses due to leakage	R_{al}	$\mathrm{kNs/m^5}$
Acoustic mass of port including air load	R_{ap}	$\mathrm{kNs/m^3}$
Acoustic resistance of port losses	M_{ap}	$\mathrm{kg/m^4}$
Mechanical mass of passive radiator diaphragm including voice coil and air load	M_{mr}	g
Mechanical stiffness of passive radiator suspension (inverse of compliance C_{mr})	K_{mr}	N/mm
Mechanical resistance of passive radiator suspension losses	R_{mr}	kg/s
Derived parameters:		
Q-factor of acoustic system at fb considering leakage losses	Q_{l}	---

Resonance frequency of enclosure-port system	f_{b}	Hz
Q-factor considering port losses	$\mathrm{Q_p}$	---
Resonance frequency of enclosure-port system	f_{f}	Hz

4.1.6 Room and Radiation

Radiation into half and full space: 2π or 4π (anechoic, piston)

Parameter	**Symbol**	**Unit**
Distance to radiation point in far field	r_{ref}	m

4.2 Results

4.2.1 Electro-dynamical Transducer

Parameter	**Symbol**	**Unit**
<u>Derived parameters:</u>		
Transducer resonance frequency (influences R_{ms} and M_{ms})	f_s	Hz
Mechanical Q-factor of driver in free air, considering R_{ms} only	Q_{ms}	---
Electrical Q-factor of driver in free air, considering R_e only	Q_{es}	---
Mechanical Q-factor of driver in free air, considering Rms only (influences R_{ms})	Q_{ts}	---
Equivalent air volume of driver suspension	V_{as}	l
<u>Efficiency and Sensitivity:</u>		
Passband efficiency of driver operated in baffle	η_{Pb}	%
Passband sensitivity of driver operated in baffle with reference voltage u_{ref} and reference distance r_{ref} defined in ppg.	L_{Pb}	dB

4.2.2 Enclosure

Parameter	**Symbol**	**Unit**
<u>Lumped parameters:</u>		
Acoustical compliance of air in enclosure	C_{ab}	$\mathrm{m^3/Pa}$
Mechanical stiffness of air in enclosure	K_{mb}	N/mm
Acoustical compliance of air in front enclosure	C_{f}	$\mathrm{m^3/Pa}$
Total acoustical compliance of transducer and enclosure	C_{at}	$\mathrm{m^3/Pa}$
Total mechanical stiffness of transducer and enclosure	K_{mt}	N/mm
System compliance ratio	α	---
<u>Derived parameters:</u>		
Resonance frequency of the closed box system	f_{c}	Hz
Passive-Radiator resonance frequency (free air)	f_{p}	Hz
Mechanical Q-factor of passive radiator in free air, considering R_{mr} only	Q_{mp}	---
Total Q-factor considering all acoustical losses	Q_{b}	---
Q-factor of the closed box system (considering system load)	Q_{tc}	---

4.2.3 State Variables and Further Characteristics (depending on stimulus)

Parameter	**Symbol**	**Unit**
Reference Voltage-Sensitivity of selected stimulus for $r_{\mathrm{ref}} = 1\ \mathrm{m}$ and $u_{\mathrm{ref}} = 1\ \mathrm{V}$ according to IEC 60268-22	L_{R}	dB
Reference efficiency for selected stimulus according to IEC 60268-22	η_{R}	%
Far field SPL at distance r_{ref} for stimulus	L_{Pfar}	dB
Terminal voltage (rms) for stimulus	$U_{\mathrm{T}_{rms}}$	V
Generator voltage (rms) for stimulus	$U_{G_{rms}}$	V
Terminal voltage (peak) for stimulus	$U_{\mathrm{T_{peak}}}$	V
Generator voltage (peak) for stimulus	$U_{G_{\mathrm{peak}}}$	V
Input current (rms) for stimulus	$I_{\mathrm{T_{rms}}}$	A
Input current (peak) for stimulus	$I_{\mathrm{T_{peak}}}$	A
Voice coil displacement (rms) for stimulus	$X_{\mathrm{c_{rms}}}$	mm

Voice coil displacement (peak) for stimulus	$X_{c_{\mathrm{peak}}}$	mm
Voice coil velocity (rms) for stimulus	$V_{c_{\mathrm{rms}}}$	m/s
SPL in rear air volume for stimulus	p_{box}	dB

4.2.4 Transfer functions

Function	Symbol	Unit
Voltage Sensitivity	$L(f)$	dB
Efficiency	$\eta(f)$	%
Electrical Impedance:		
Total electrical impedance	$Z_{\mathrm{e}}(f)$	Ω
Back EMF	Blv/u_{g}	Ω
DC-Resistance of the transducer and the amplifier output resistance	$R_{\mathrm{e}} + R_{\mathrm{g}}$	Ω
Voice coil impedance	$Z_{\mathrm{el}}(f)$	Ω
Far Field Sound Pressure:		
Total Sound Pressure	$H_{\mathrm{pfar}}(f,r)$	dB
Contribution from port	$H_{\mathrm{p}}(f,r)$	dB
Target sound pressure	$H_{\mathrm{t}}(f,r)$	dB
Total active system (with equalization)	$H_{\mathrm{total}}(f,r)$	dB
Displacement divided by generator voltage:		
Voice coil	$x_{\mathrm{c}}(f)/u_{\mathrm{g}}$	dB
Passive radiator	$x_{\mathrm{r}}(f)/u_{\mathrm{g}}$	dB
Velocity divided by generator voltage:		
Voice coil	$v_{\mathrm{c}}(f)/u_{\mathrm{g}}$	dB
Passive radiator	$v_{\mathrm{r/p}}(f)/u_{\mathrm{g}}$	dB
Force divided by generator voltage:		
At the motor	$F_{\mathrm{c}}(f)/u_{\mathrm{g}}$	dB
At M_{ms}	$F_{\mathrm{Mms}}(f)/u_{\mathrm{g}}$	dB
At R_{ms}	$F_{\mathrm{Rms}}(f)/u_{\mathrm{g}}$	dB
At C_{ms}	$F_{\mathrm{Cms}}(f)/u_{\mathrm{g}}$	dB
Into the acoustical system	$F_{\mathrm{L}}(f)/u_{\mathrm{g}}$	dB
Volume velocity divided by generator voltage:		
From S_d	$q_{S_{\mathrm{d}}}(f)/u_{\mathrm{g}}$	dB
Into C_{ab}	$q_{\mathrm{c}}(f)/u_{\mathrm{g}}$	dB
Into C_f	$q_{\mathrm{f}}(f)/u_{\mathrm{g}}$	dB
Into R_{al}	$q_{\mathrm{l}}(f)/u_{\mathrm{g}}$	dB
Into port/passive radiator	$q_{\mathrm{p}}(f)/u_{\mathrm{g}}$	dB
Amplifier transfer function (voltage drop)	$u_{\mathrm{t}}(f)/u_{\mathrm{g}}$	dB
Prefilter transfer function (Equalizer)	$\mathrm{H}_{\mathrm{equ}}(f)$	dB
Stimulus Spectrum:		
Relative input spectrum	$G_{\mathrm{w}}(f)$	dB
Aligned input spectrum	$G_{\mathrm{eq}}(f)$	dB
Voltage Spectrum:		
Terminal voltage	u_{t}	dB
Amplifier output voltage without load	u_{g}	dB
Power Spectrum:		
Electrical generator output power	P_{e}	dB
Acoustical output power	P_{a}	dB
Power dissipation in amplifier	$P_{R_{\mathrm{g}}}$	dB
Spectrum of the sound pressure level	L_{pfar}	dB
State Spectrum:		
Voice Coil Displacement	$L_{x_{\mathrm{coil}}}$	dB
Voice Coil Velocity	$L_{v_{\mathrm{coil}}}$	dB
Voice Coil Force	$L_{F_{\mathrm{coil}}}$	dB
Radiated Volume Velocity	L_{q_a}	dB

5 References

5.1 Related Modules	*LPM* Linear Parameter Measurement *SIM* Simulation *SIM-AUR* Simulation / Auralization
5.2 Manuals	*LSIM* Manual, as provided with dB-Lab 210.560 or higher
5.3 Related Papers	Wolfgang Klippel: "Green Speaker Design (Part 1: Optimal Use of System Resources)" , 2019, Klippel GmbH Wolfgang Klippel: "Green Speaker Design (Part 2: Optimal Use of Transducer Resources)" , 2019, Klippel GmbH R. H. Small: "Closed-Box Loudspeaker Systems", 2006, School of electrical Engineering, The University of Sydney, Australia

Find explanations for symbols at:
http://www.klippel.de/know-how/literature.html
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