Linear Simulation (LSIM) S58

Module of the KLIPPEL ANALYZER SYSTEM (Document Revision 1.5)

PRELIMINARY SPECIFICATION
This specification is preliminary and is subject to change.

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

CONTENT

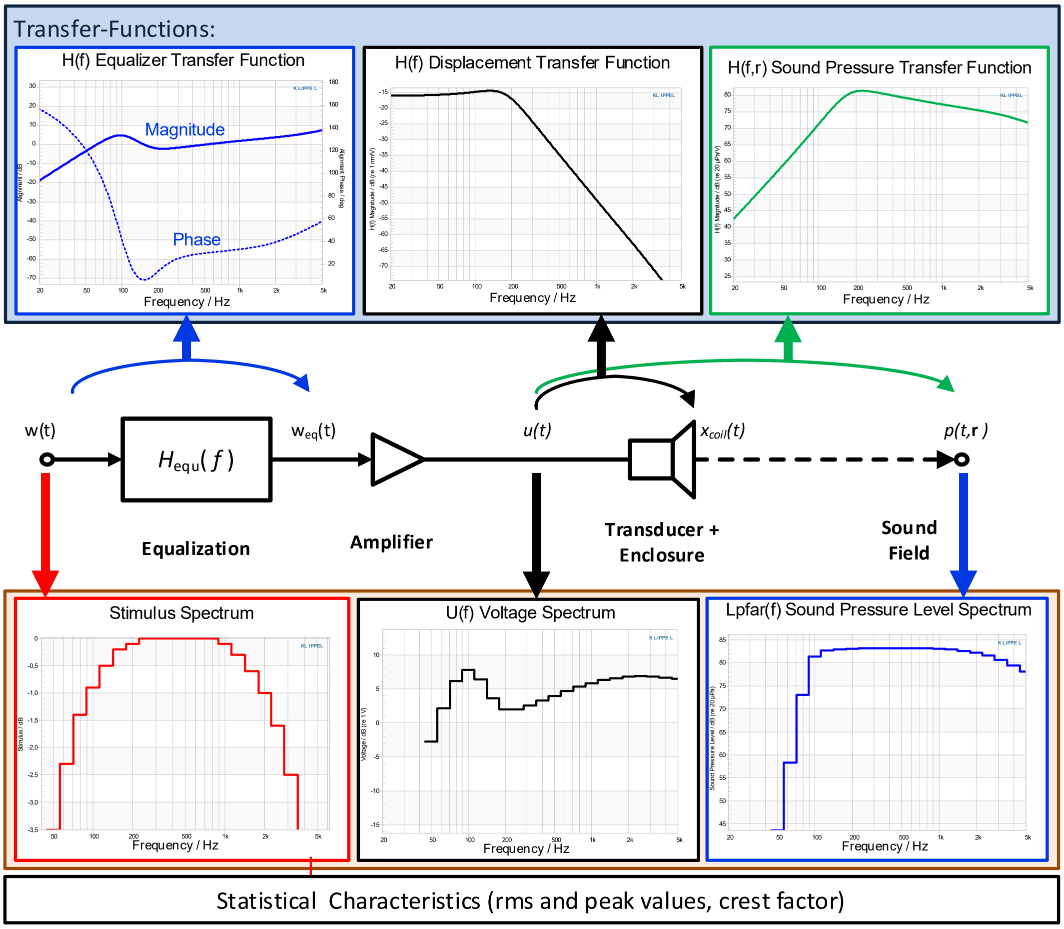
1 Overview

1.1 Principle

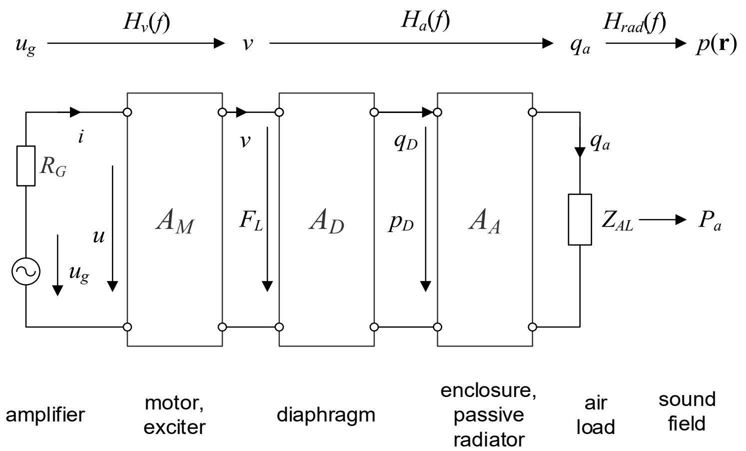
Basic Principle

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 $Z_{el}(f)$, as well as efficiency $\eta(f)$ and voltage sensitivity can be easily simulated.

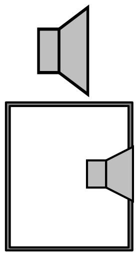
Note that the *LSIM* module only simulates the linear behavior of the system, which is considered valid at small amplitudes. Please see *SIM Simulation* or *SIM-AUR Simulation / Auralization* for nonlinear modeling.

1.2 Input

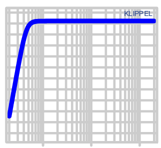
Input Parameters

The *LSIM* input is structured into 4 categories:

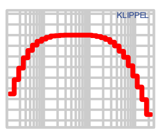
- Transducer:
  - Linear transducer parameters (free air)



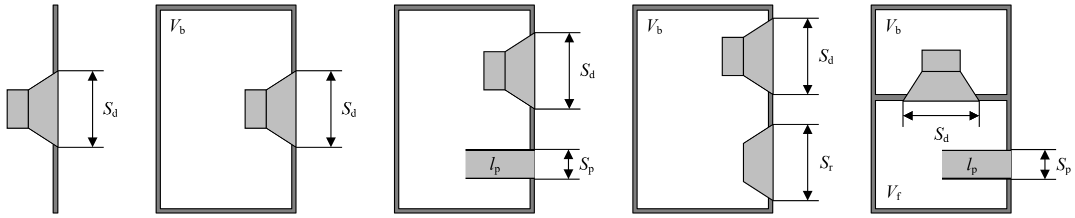
- Enclosure:
  - Type
  - Geometrical properties or lumped parameters
- Equalization:
  - High pass filter alignment
  - User defined transfer behavior



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

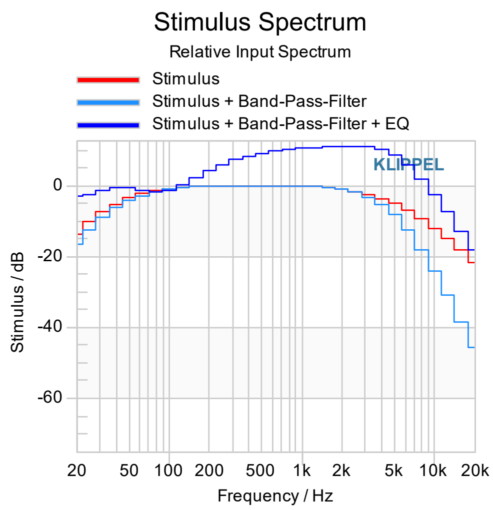


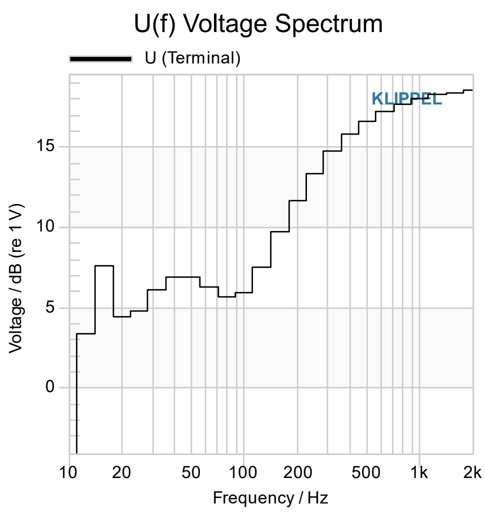
The *LSIM* supports the following enclosure types:

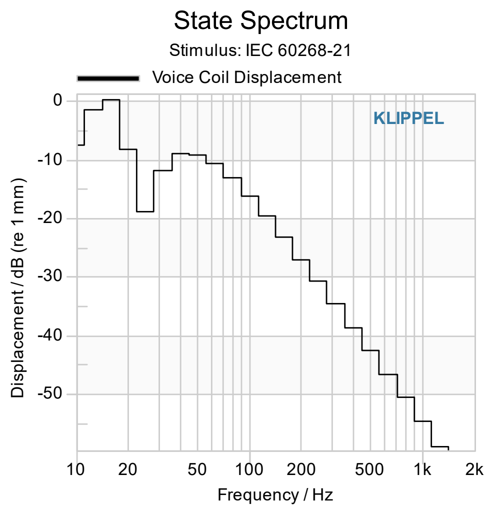
	 Baffle — Closed Box — Vented Box — Passive Radiator Box — Bandpass System

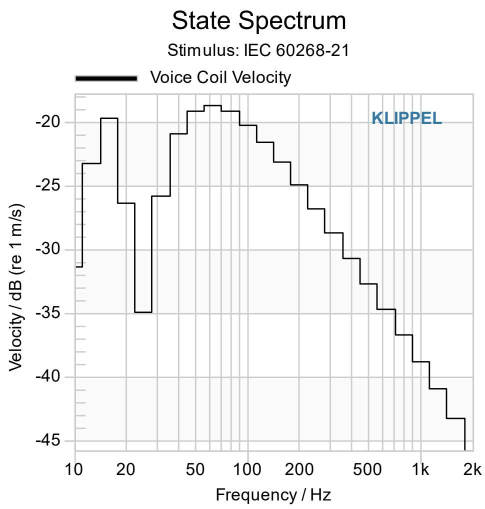
1.3 Results

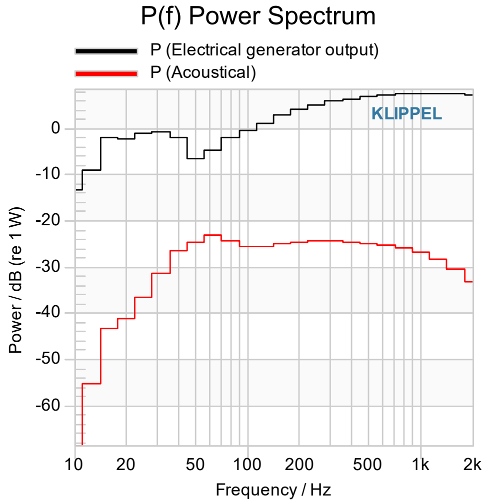
Linear Transfer Functions	The magnitude and phase frequency responses are calculated between the following state variables • Sound pressure level $L_{\mathrm{p}}(f, \boldsymbol{r})$ in far field • Displacement (voice coil, passive radiator) • Velocities (voice coil, passive radiator) • Forces in the 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)

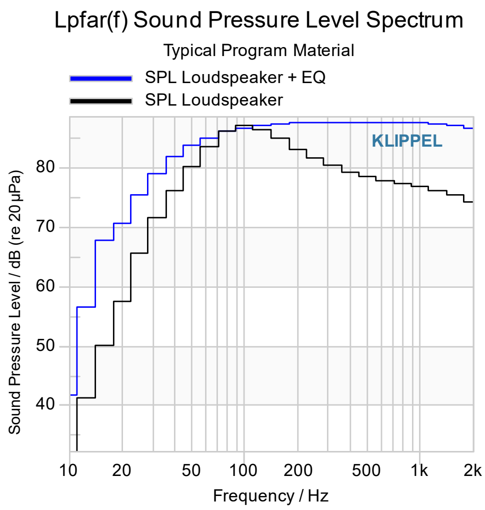












Single values

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} Mean voltage sensitivity
- L_{R} Mean efficiency

	• P_e Total electrical transducer input power • P_a Total acoustical output power

2 Example

2.1 Simulation of a vented 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 for this example is, to use the *LSIM* for designing a closed box loudspeaker. Therefor the following targets are defined:

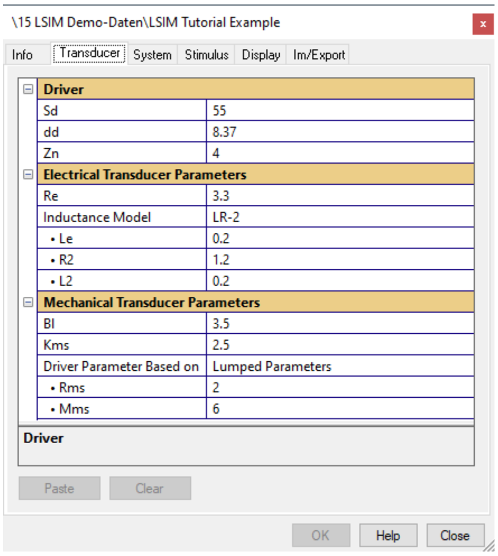
- The desired SPL output is 95 dB.
- The peak displacement for typical music stimuli should be below x_{max} = 3.5 mm.

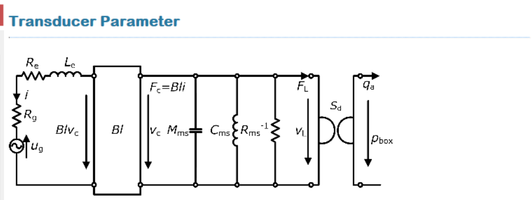
Due to the targets, the following critical single values should be determined for using typical music signals:

- Power and voltage consumption (required for selecting an optimal fitting amplifier)
- Efficiency and voltage-sensitivity
- Peak displacement

User Input

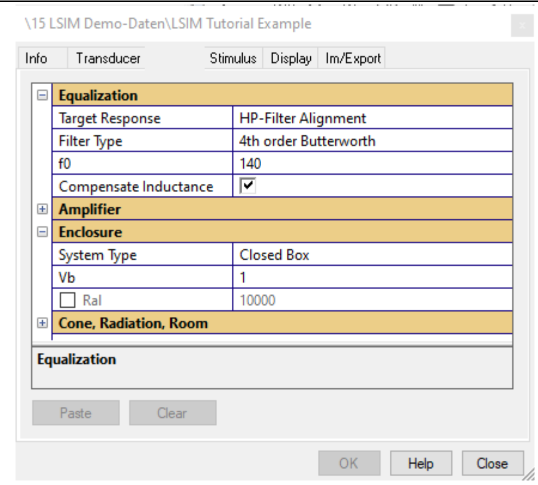
1. Linear Transducer Parameters: For this example, data of a small midrange speaker was imported from an LPM operation. Immediately after entering all data, the window *Table Transducer Parameters* shows all loudspeaker parameters. Additional to the entered data some parameters like C_{mes}, f_s and the passband-efficiency of the transducer in free air are calculated and shown.

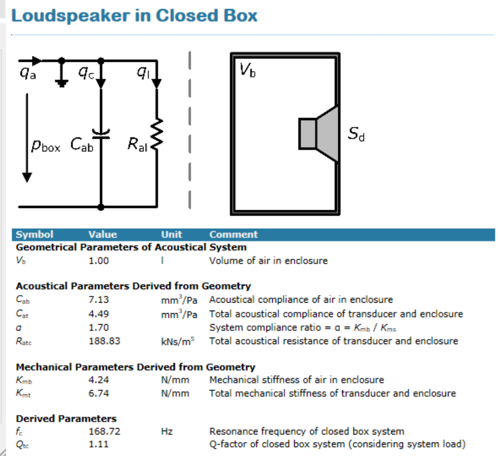




Symbol	Value	Unit	Comment
Lumped Parameters			
S_d	55.00	cm²	Effective radiation surface (fundamental mode)
Z_n	4.00	Ω	Nominal impedance rated by manufacturer
R_e	3.30	Ω	Electrical voice coil resistance at DC
L_e	200.00	μH	Voice coil inductance
R_2	1.20	Ω	Electrical resistance due to eddy current losses (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_{Pb}	0.172	%	Passband efficiency of driver operated in baffle
L_{Pb}	85.187	dB	Passband sensitivy of driver operated in baffle (u_{ref} = 1 V; r_{ref} = 1 m)

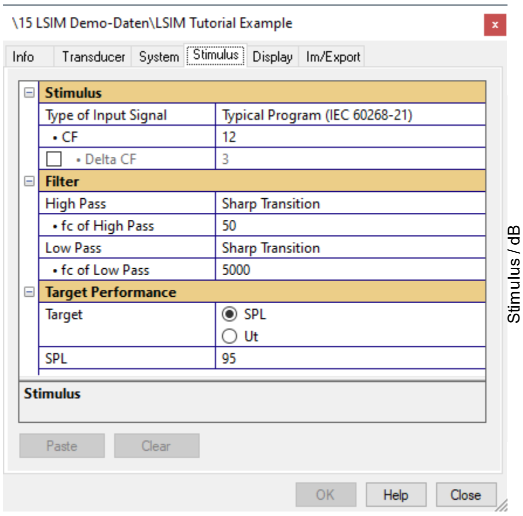
2. System parameters: For this example, a closed box loudspeaker is specified with a volume of 1 l. For defining the target transfer-behavior, the option *HP-Filter Alignment* is used. A 4th order Butterworth filter with a cutoff-frequency of 100 Hz is entered. For simplification, no amplifier output resistance R_g, Resistance due to leakage R_{al} 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.

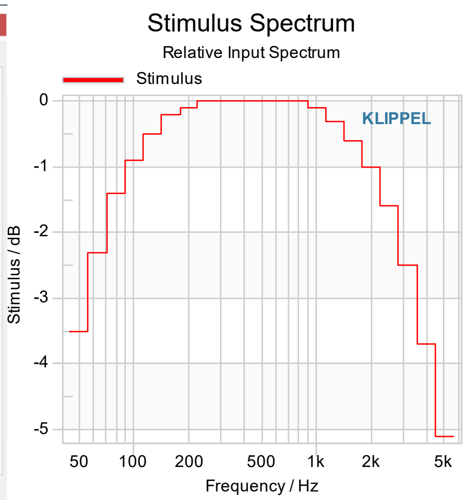




3. Stimulus Parameters: In property-page *Stimulus* the stimulus which is used for simulating the active loudspeaker is specified. The spectrum defined in IEC 60268-21 is a well representation of common broadband music stimuli and due to this well suited for simulation. A typical crest factor is 12 dB. For the specified small midrange-speaker only the frequency-band from 50 Hz to 5 kHz is interested. Below 50 Hz the expected SPL output is neglectable. Above 5 kHz nonlinear effects on the membrane will become dominant. This limitation is entered in section *Filter*. As target performance the previously desired 95 dB are entered for *Target SPL*.

   The window stimulus spectrum immediately after defining the stimulus parameters shows the stimulus spectrum. All spectra in this window are relative and not normalized or referenced. After clicking on *run* the band-pass filtered and equalized spectrum is visible as well.





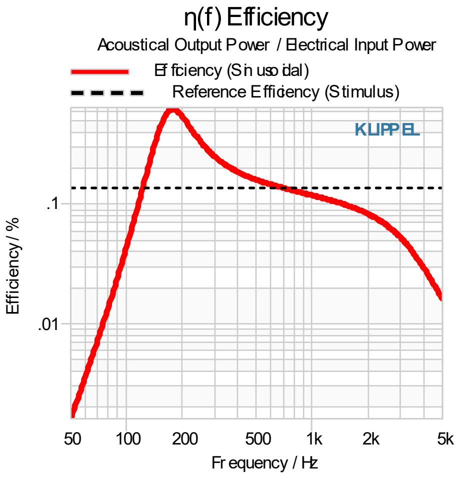
Results

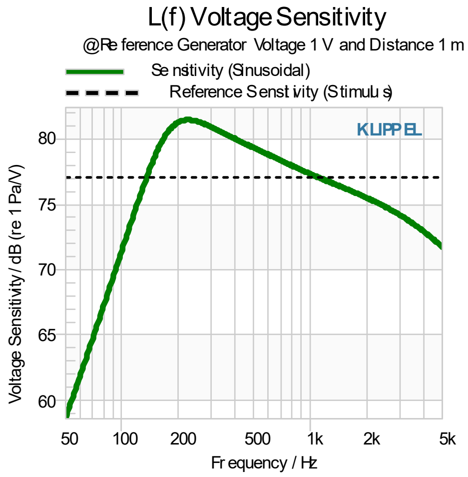
The single values listed in table State Variables provides most important information considering the simulated music reproduction:

1. For generating 95 dB SPL output using the desired broadband signal, a voltage of 7.85 V (rms) and current of 1.62 A (rms) are required.
2. The resulting reference efficiency is 0.136 % and the reference voltage-sensitivity is 77.1 dB.
3. Due to the specified crest factor, the amplifier has to provide round about 12.43 W with a peak voltage of 31.27 V.
4. For the specified stimulus a peak displacement of 1.85 mm is expected.

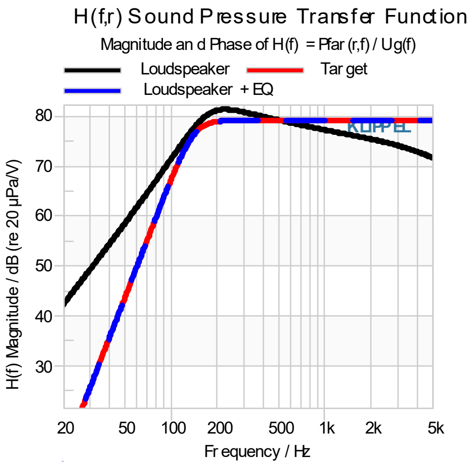
Those single values are the basis for defining the amplifier and transducer requirements. Checking the limits defined in the task above reveals, that the desired SPL is possible without of crossing the displacement limit of 3.5 mm.

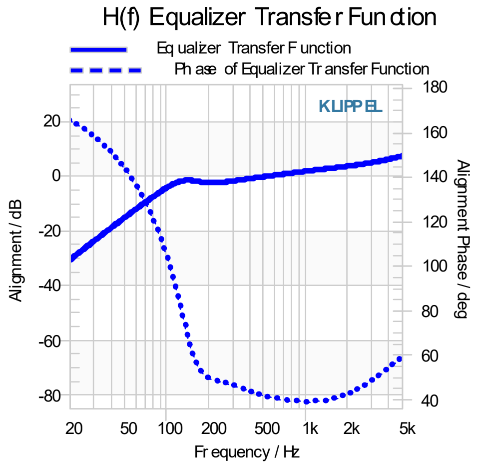
Viewing the curves efficiency and voltage sensitivity versus frequency is useful to check out the limitations of the passive loudspeaker system. The efficiency at lower frequencies decreases rapidly, so pushing frequencies below 100 Hz will be inefficient. Pay attention: Efficiency and voltage-sensitivity are not equal. Efficiency shows the ratio between incoming and outgoing power in percent. Voltage-sensitivity shows the SPL-output at 1 m distance, which is accessible for 1 V at the loudspeaker terminal.





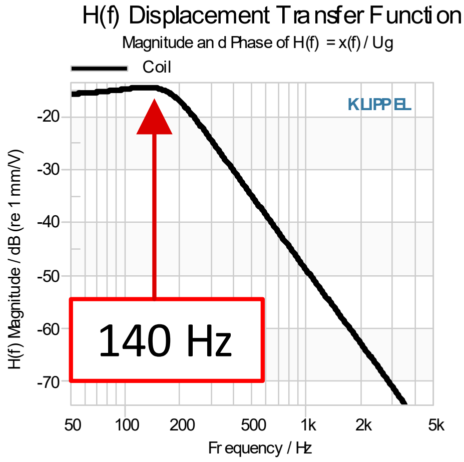
For detailed investigations it is useful to view transfer-functions and spectra. It is recommended to check if equalization was reasonable adjusted. Therefor the window *H(f,r) Sound Pressure* and *H(f) Equalizer* are relevant:

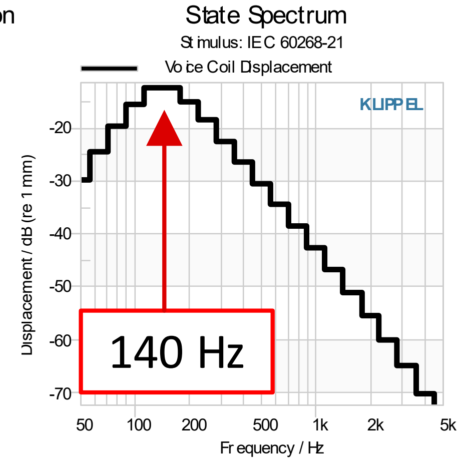




In the left diagram above the sound pressure transfer function of the passive (black) and active loudspeaker including equalization (blue) is visible. Additional to this the target transfer behavior is shown (red). Comparing the black and blue curve shows a reasonable target transfer behavior. This can be approved by viewing the equalizer transfer function (right diagram above). The transfer function contains no excessive damping or boosting.

For active loudspeakers displacement is a critical issue. High displacement results undesired distortion and is a limiting factor especially for active control. For investigating this, the displacement transfer-function and displacement spectrum are useful.

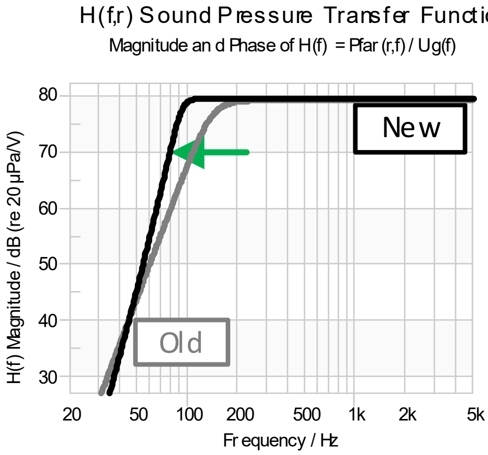


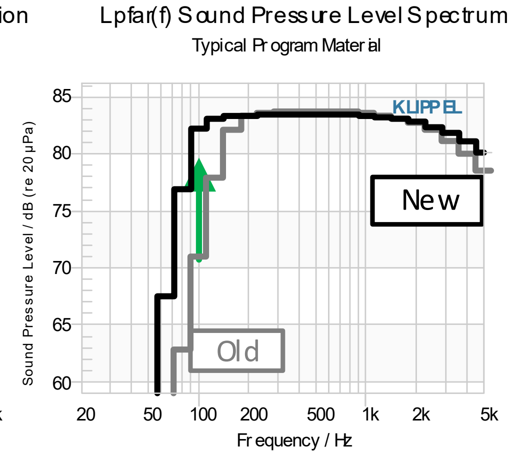


The voice-coil displacement transfer function reveals a maximum at 140 Hz. This is slightly below the resonance frequency of the loudspeaker in the enclosure. Above 140 Hz the displacement decreases significantly. Below 140 Hz the displacement decreases only slightly and converge at -16 dB. For the given broadband stimulus, we can derive a maximum in the displacement spectrum of 0.24 mm in the frequency band around 140 Hz.

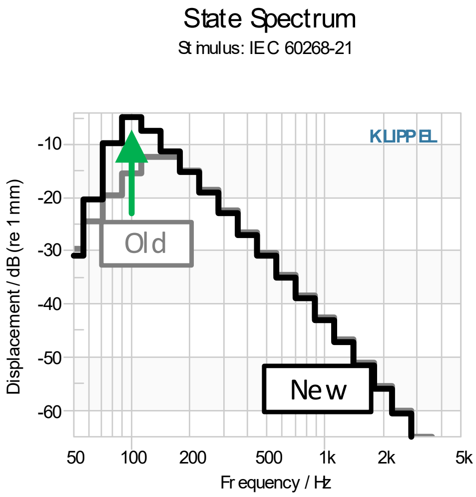
Alternative Design

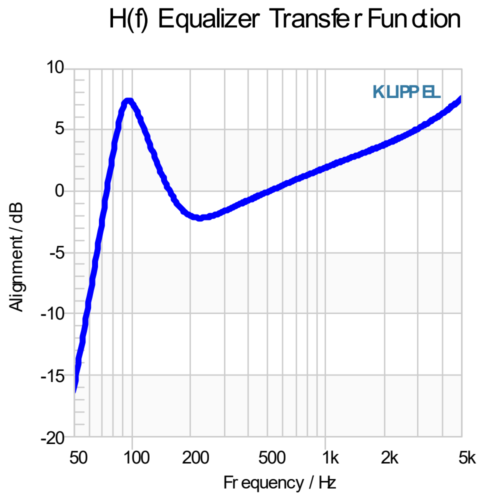
For this example-loudspeaker, an alternative design should be found to enlarge the base-reproduction. The LSIM module provides a lot of approaches to do this. This example focuses on equalization. Finding an optimal target high-pass characteristic is important. Setting the cutoff-frequency too low will result an inefficient system prone to extreme displacement requirements. A high cut-off frequency in the target transfer behavior results low base reproduction, which is usually not desired.
In this case the cutoff-frequency is slightly decreased from 140 Hz to 90 Hz and the filter type and order is changed to a 6^{th} order Chebyshev filter to generate a higher slope below the cut-off frequency. Applying these changes results a slightly increase of input-voltage to get the desired 95 dB SPL output. (Old settings: $U_T = 7.85$ V; New settings: $U_T = 8.47$ V) The peak displacement is increased by 1.59 mm and with 3.44 mm slightly below the specified displacement-limit.
Viewing the changes in the sound pressure transfer function as well as sound pressure spectrum shows a significant increase around 100 Hz of 10 dB.





Major reason for this change is the boots of the equalizer-filter at around 100 Hz. This boost is also well visible in the displacement spectrum.





Comparing the reference efficiency and reference voltage sensitivity reveals that the base enhancement results a more inefficient loudspeaker:

- $L_{R,\,old} = 77.1$ dB; $\eta_{R,\,old} = 0.136$ %;
- $L_{R,\,new} = 76.44$ dB; $\eta_{R,\,old} = 0.119$ %;

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 dia-phragm	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
Derived parameters:		
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
Efficiency and Sensitivity:		
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
Lumped parameters:		
Acoustical compliance of air in enclosure	C_{ab}	m^3/Pa
Mechanical stiffness of air in enclosure	K_{mb}	N/mm
Acoustical compliance of air in front enclosure	C_f	m^3/Pa
Total acoustical compliance of transducer and enclosure	C_{at}	m^3/Pa
Total mechanical stiffness of transducer and enclosure	K_{mt}	N/mm
System compliance ratio	α	---
Derived parameters:		
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 $r_{ref} = 1$ m and $u_{ref} = 1$ 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	$U_{T_{rms}}$	V
Generator voltage (rms) for stimulus	$U_{G_{rms}}$	V
Terminal voltage (peak) for stimulus	$U_{T_{peak}}$	V
Generator voltage (peak) for stimulus	$U_{G_{peak}}$	V
Input current (rms) for stimulus	$I_{T_{rms}}$	A
Input current (peak) for stimulus	$I_{T_{peak}}$	A
Voice coil displacement (rms) for stimulus	$X_{c_{rms}}$	mm
Voice coil displacement (peak) for stimulus	$X_{c_{peak}}$	mm
Voice coil velocity (rms) for stimulus	$V_{c_{rms}}$	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	$Z_e(f)$	Ω
Back EMF	Blv/u_g	Ω
DC-Resistance of the transducer and the amplifier output resistance	$R_e + R_g$	Ω
Voice coil impedance	$Z_{el}(f)$	Ω
Far Field Sound Pressure:		
Total Sound Pressure	$H_{pfar}(f,r)$	dB
Contribution from port	$H_p(f,r)$	dB
Target sound pressure	$H_t(f,r)$	dB
Total active system (with equalization)	$H_{total}(f,r)$	dB
Displacement divided by generator voltage:		
Voice coil	$x_c(f)/u_g$	dB
Passive radiator	$x_r(f)/u_g$	dB
Velocity divided by generator voltage:		
Voice coil	$v_c(f)/u_g$	dB
Passive radiator	$v_{r/p}(f)/u_g$	dB
Force divided by generator voltage:		
At the motor	$F_c(f)/u_g$	dB
At M_{ms}	$F_{Mms}(f)/u_g$	dB
At R_{ms}	$F_{Rms}(f)/u_g$	dB
At C_{ms}	$F_{Cms}(f)/u_g$	dB
Into the acoustical system	$F_L(f)/u_g$	dB
Volume velocity divided by generator voltage:		
From S_d	$q_{S_d}(f)/u_g$	dB
Into C_{ab}	$q_c(f)/u_g$	dB
Into C_f	$q_f(f)/u_g$	dB
Into R_{al}	$q_l(f)/u_g$	dB
Into port/passive radiator	$q_p(f)/u_g$	dB
Amplifier transfer function (voltage drop)	$u_t(f)/u_g$	dB
Prefilter transfer function (Equalizer)	$H_{equ}(f)$	dB
Stimulus Spectrum:		
Relative input spectrum	$G_w(f)$	dB
Aligned input spectrum	$G_{eq}(f)$	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_g}	dB
Spectrum of the sound pressure level	L_{pfar}	dB
State Spectrum:		
Voice Coil Displacement	$L_{x_{coil}}$	dB
Voice Coil Velocity	$L_{v_{coil}}$	dB
Voice Coil Force	$L_{F_{coil}}$	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
Last updated: May 25, 2021