Simulation (SIM) Version 2 S3

Software Module of the KLIPPEL ANALYZER SYSTEM

FEATURES

- Numerical exploration of large signal behavior of speaker systems
- Considers nonlinearities in driver, enclosure and radiation
- Nonlinear parameters can be easily manipulated with an professional curve editor
- Vented, sealed box, passive radiator, bandpass and general enclosure
- Incorporates crossover, cone, radiation and room frequency response
- Sophisticated nonlinear thermal model that considers forced air convection cooling
- Two-tone excitation signal
- Calculates electrical, mechanical and acoustic state signals (waveform and spectrum)
- Calculates voice coil, gap and magnet temperature
- Shows results versus frequency and voltage
- Reveals the large signal mechanism in detail
- Separates the effects of the individual nonlinearities
- Finds dominant sources of distortion
- Determines maximal output
- Shows mechanical and thermal load
- Helps to improve performance/cost ratio
- Saves time and cost in prototyping

This module performs a numerical simulation of electro-dynamical drivers mounted in common enclosure systems. An extended lumped-parameter model is used to describe the transfer behavior in the full working range. The input of this routine are the parameters of a real or fictitious driver and enclosure system. The dominant nonlinearities of the driver (motor and suspension), the enclosure (air compression, port losses, passive radiator suspension) and radiation (Doppler effect) are considered. For a two-tone excitation signal the responses of electrical, mechanical and acoustical variables are calculated. A spectral analysis applied to the steady-state signals shows the DC component and magnitude and phase of the fundamental, the generated distortion components and the temperatures of the voice coil, the gap and the magnet.

A series of measurements can be performed to investigate the voltage and/or frequency characteristics of distortion components and distortion measures.

Each nonlinearity in the system can be switched on and off to investigate its effect systematically. This way the dominant sources of distortion are identified. Furthermore mechanism behind the large signal behavior are revealed in detail. This gives valuable indications for driver optimization. A professional curve editor supports the modification of the driver nonlinearities to stimulate new ideas in the initial development stage.

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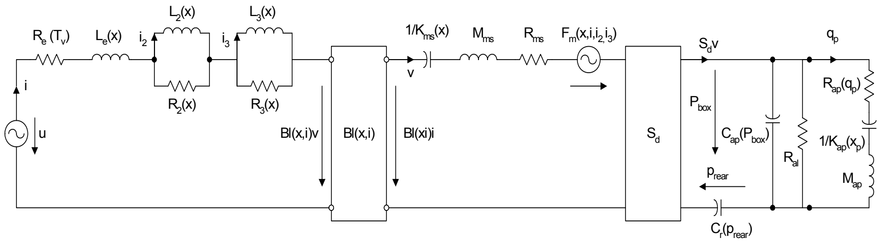
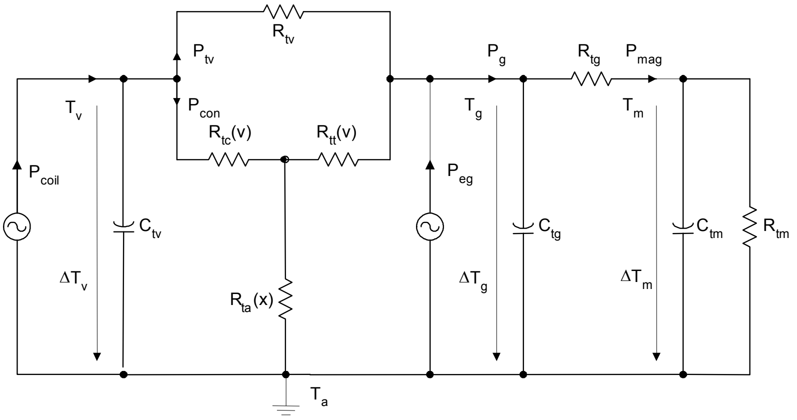
Large Signal Modeling

Equivalent Circuit



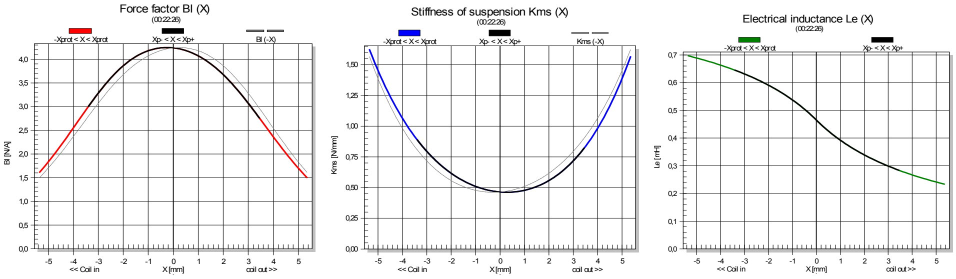
The lumped-parameter model shown above is used to describe the large signal behavior of electro-dynamical transducers mounted in common acoustical systems (sealed or vented enclosure, passive radiator, bandpass). In contrast to the well known linear model the components of the large signal model are not constant but rather depend on one or more speaker states (like displacement x, voice coil temperature T_v, sound pressure p_{box}, volume velocity q_p in the port).

Thermal Modeling



The heating of the voice coil is modeled by a nonlinear thermal equivalent circuit. The model describes the heat transfer from the voice coil to the pole tips and the magnet. It considers convection cooling (dependent on cone displacement and velocity) and direct heating of voice coil and magnet due to eddy currents.

Parameters



The linear, nonlinear and thermal parameters of the driver can be identified with the *Large Signal Identification* module (LSI Pro) which is part of the KLIPPEL ANALYZER SYSTEM. All of the driver parameters may be copied to the clipboard and imported to SIM. The type and the parameters of the enclosure and radiation conditions may be specified. No import parameters are required to consider the nonlinear compliance of the air in the enclosure and nonlinear radiation due to the Doppler effect. This module also provides a professional curve editor to modify the shape of the nonlinearities and to investigate the performance of design choices.

Simulation Technique

Signal Generation

Stimulus	A two tone signal defined by $U(t) = U_1 \sin(2\pi f_1 t) + U_2 \sin(2\pi f_2 t)$ is an optimal excitation signal to measure harmonic, difference-tone and summed-tone intermodulation components. The frequencies f_1 and f_2 and the voltage U_1 and U_2 may be specified by the user. They may be varied automatically to perform frequency and voltage sweeps, and combined voltage/frequency sweeps.
Pre-Filter	The excitation signal $u(t)$ may be modified by pre-filter. This is useful to include crossovers into the simulation. The frequency response $H_{pre}(f)$ (magnitude and phase vs. frequency) of the filter can be imported.
Frequency Sweep	The user can choose between a single point measurement performed with constant f_1 and a series of sequential measurements performed for different values of f_1. The user has to specify the start value f_{start} and the end value f_{end} for the frequency f_1 as well as the number of intermediate points spaced linearly or logarithmically.
Voltage Sweep	The user can choose between a single point measurement performed with constant voltage U_1 and a series of sequential measurements performed for different values of U_1. The user has to specify the start value U_{start} and the end value U_{end} for the Voltage U_1 as well as the number of intermediate points spaced linearly or logarithmically. The voltage U_2 of the second tone is coupled to the voltage U_1 of the first tone and the user specifies the ratio U_2/U_1.
Measurement of Harmonics	The user can choose between four measurement modes, i.e. • Harmonics, • Harmonics + Intermodulations (f1), • Harmonics + Intermodulations (f2), • Intermodulations (f1). The “Harmonics” mode is used to measure the harmonic components of tone f_1. The second excitation tone is switched off. This reduces the amplitude of the excitation signal $U(t)$ and avoids interferences between harmonic and intermodulation components.
Measurement of Intermodulations	In the “Harmonics + Intermodulation (f1)” and “Harmonics + Intermodulation (f2)” modes summed-tone and difference-tone intermodulation components (centred around f_1 and f_2 respectively) are measured additionally to the harmonic components of f_1. No harmonic components are measured if “Intermodulations (f1)” is selected. There are three different ways to specify the frequency f_2 of the second tone: • f_2 = const. The user specifies the frequency f_2 which is held constant during frequency sweep of f_1. This mode allows to generate a very critical stimulus for most transducers. Selecting $f_2 < f_1$, f_2 may represent a bass tone producing large voice coil displacement and f_1 represents any audio component (voice) in the pass band of the transducer. • f_2/f_1 = const. The user specifies the frequency ratio between both excitation tones. Selecting $f_2 > f_1$ and using a fractional ratio (e.g. 5.5) this mode avoids interferences between the harmonic and intermodulation distortion components. • f_2-f_1 = const. The user specifies the distance between both excitation frequencies. This mode produces difference intermodulation at the same frequency independent of f_1.

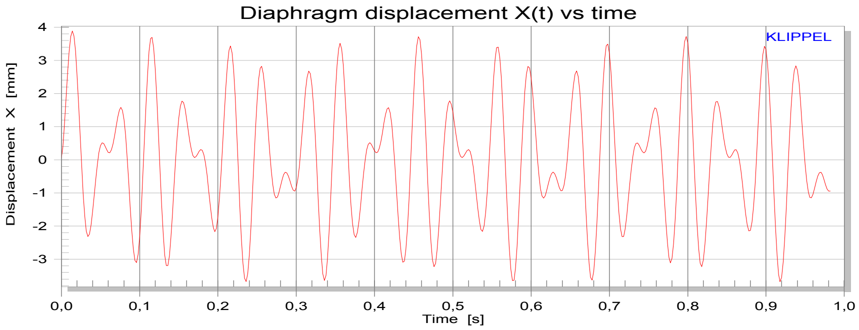
Sample Rate

The excitation signal is sampled at 48 kHz to simulate the transducer up to 24 kHz signal components.

Solving the Differential Equation

Numerical Integration

The large signal model with the specified driver and enclosure parameters is excited by the generated two-tone signal. The electrical, mechanical and acoustic state variables of the model are calculated by numerical integration and their waveform may be viewed versus time.



Separation

To find the dominant source of distortion and to investigate design choices the following nonlinearities might be enabled or disabled during simulation:

- motor nonlinearity due to $Bl(x)$
- mechanical suspension nonlinearity due to $K_{ms}(x)$
- inductance nonlinearity due to $L_e(x)$
- nonlinearity of para-inductance $L_2(x), L_3(x)$
- nonlinearity of resistance $R_2(x)$, $R_3(x)$ due to eddy current losses
- reluctance force F_m (electromagnetic drive)
- adiabatic compression in enclosure $C_{ab}(p_{box})$
- adiabatic compression of rear enclosure $C_r(p_{rear})$
- nonlinearity of port losses $R_{ap}(v_p)$
- nonlinearity of passive radiator suspension losses $R_{mp}(v_p)$
- passive radiator stiffness nonlinearity $K_{mp}(x_p)$
- radiation distortion (Doppler effect)

Initial Conditions

The displacement of the voice coil at the beginning of the numerical integration may be specified by the user to investigate the stability of the driver. Performing two simulations with varied initial displacement ($x(t=0)=x_{max}$ and $x(t=0)= -x_{max}$) reveal critical frequencies where the driver bifurcates into different solutions.

Cone, radiation, room

Two different ways to calculate the sound pressure P_{far} in the far field are supported. The first one is to use a simple model that assumes a piston like cone and “ideal” 2π-or 4π-radiation without any deterioration of the rooms. The second option is to import the total frequency response $H_{total}=P_{far}(f)/U(f)$ which may either be measured or synthesized.

Heating of Coil, Pole Tips and Magnet

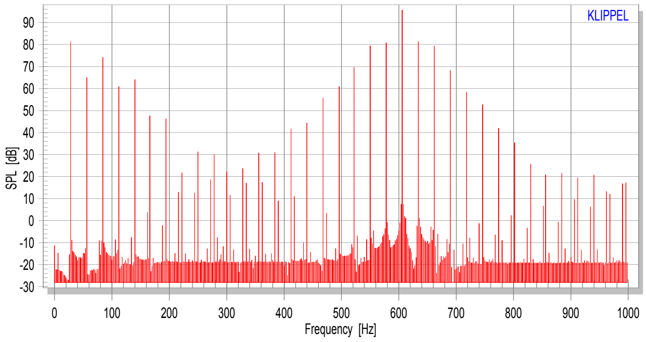
Simultaneously with the solution of the electrical, mechanical and acoustical system the steady state temperature of the voice coil, the pole tips and the magnet will be predicted using the nonlinear thermal model and the thermal parameters. Two different simulation modes are supported. The first mode simulated the short term thermal behavior. It is assumed that the voice coil temperature has reached steady state while the magnet is still cold. The second mode is for investigating the long term thermal behavior. Both the voice coil and the magnet are assumed to be hot and in steady state.

Different Solvers

Different algorithms for the numerical integration are provided. The user may choose either a fast solver with fixed step size or a more sophisticated solver with step size control giving higher precision. If the system behaves stiff a special solver that can cope with the problem will be used in both cases.

Spectral Analysis

Spectrum



Distorted sound pressure response of a two tone excitation signal

The steady state driver variables are subject to a FFT analysis. Since the frequencies f_1 and f_2 of the excitation tones correspond with the FFT length additional windowing of the time signal can be omitted. This reveals the spectral components without any smearing effects.

Data Compression

The magnitudes and phases of spectral components which are of particular interest such as fundamental, DC-component and the harmonic and intermodulation components up to the specified order *n* are stored in the database only and may be listed.

Pause

A series of measurements may be paused to view details of the waveform and in the spectrum.

Results

Time Signals (Speaker States)

- Cone displacement vs. time
- Cone velocity vs. time
- Input current vs. time
- Voltage at terminals vs. time
- Passive radiator displacement vs. time
- Volume velocity in port vs. time
- Pressure in enclosure vs. time
- Sound pressure in far field vs. time

Spectra (Speaker States)

- Spectrum of cone displacement
- Spectrum of cone velocity
- Spectrum of input current
- Spectrum of voltage at terminals
- Spectrum of passive radiator displacement vs. time
- Spectrum of volume velocity in port
- Spectrum of pressure in enclosure
- Spectrum of sound pressure in far field

Peak and Bottom Values of Selected Speaker States *)

- Peak and bottom value of waveform vs. frequency f_1 and voltage U_1 of excitation

Spectral Components of Selected Speaker States *)

- DC component vs. frequency f_1 and voltage U_1 of excitation
- Fundamental component vs. frequency f_1 and voltage U_1 of excitation
- *n*th-order harmonic distortion component vs. frequency f_1 and voltage U_1 of excitation
- *n*th-order summed frequency modulation component vs. frequency f_1 and voltage U_1 of excitation
- *n*th-order difference frequency modulation component vs. frequency f_1 and voltage U_1 of excitation
- Compression (= Fundamental $\cdot$ U_{start} / U_1) vs. frequency f_1 of excitation

Relative Distortion (IEC DIN 60268) of Selected Speaker States *)

Total harmonic distortion in percent vs. frequency f_1 and voltage U_1 of excitation

Second-order harmonic distortion in vs. frequency f_1 and voltage U_1 of excitation

Third-order harmonic distortion in percent vs. frequency f_1 and voltage U_1 of excitation

Second-order modulation distortion in percent vs. frequency f_1 and voltage U_1 of excitation

Third-order modulation distortion in percent vs. frequency f_1 and voltage U_1 of excitation

Additional Distortion Measures for Selected Speaker States *)

Weighted harmonic distortion (Hi-2, Blat) distortion

Amplitude modulation distortion (called IMD in automotive applications) given as RMS, top and bottom value

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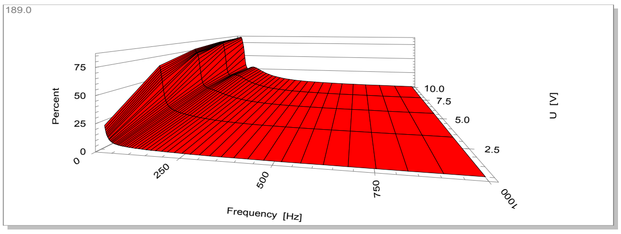
*) The user may switch between the speaker states cone displacement, cone velocity, input current, voltage at terminals, passive radiator displacement, volume velocity in port, pressure in enclosure and sound pressure in far field

Graphical Representation

Example: Harmonic distortion in radiated sound pressure versus frequency and voltage

3D-Graphic

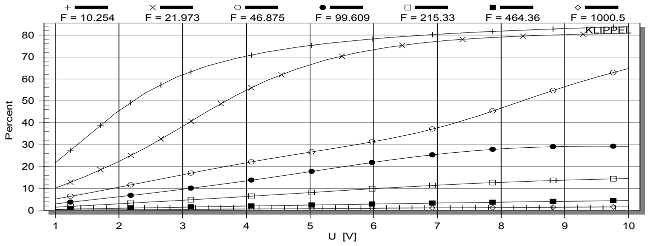
Performing a simulation with voltage and frequency sweep spectral and distortion components may be displayed in a 3D-plot versus frequency f_1 and voltage U_1 of the first excitation tone. Viewing the plot from different perspectives is convenient for interpreting the data. An additional contour plot may be activated.



2D-Graphic

(versus U)

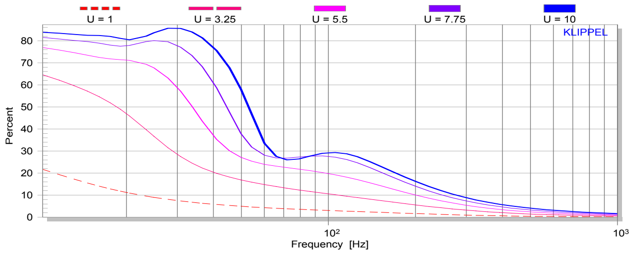
Spectral and distortion components may be displayed as 2D plot versus excitation voltage U_1 .This representation shows the nonlinear relationship between input and output amplitude (compression and expansion). The results for different excitation frequencies f_1 are represented by different curves.



2D-Graphic

(versus f)

Spectral and distortion components may be displayed as 2D plot versus excitation frequency f_1. The results for different excitation voltages U_1 are represented by different curves. The ordinate of the plot is by default scaled linearly (logarithmically) if the samples in the U_1 voltage sweep are spaced linearly (logarithmically). This way the frequency responses of a linear system measured at different voltages will appear as multiple equally spaced curves. Amplitude compression and expansion due to thermal and nonlinear mechanisms can therefore be detected easily .



Input Parameters

Driver Parameters	Symbol	Min	Typ	Max	Unit
DC resistance of cold voice coil	R_e	0.01			Ω
Moving mass including air load	M_{ms}	0.001		5000	g
Mechanical resistance of suspension losses	R_{ms}	> 0		10000	Ns/m
Resonance frequency	f_s	1		1000	Hz
Mechanical loss factor	Q_{ms}	0.01			
Force factor (Bl product)	Bl	0.1			N/A
Stiffness of suspension	K_{ms}	> 0		100	N/mm
Voice coil inductance	L_e	0.01			mH
Electrical resistance due to eddy current losses	R_2, R_3	0.01			Ω
Voice coil para-inductance	L_2, L_3	0.01			mH
Coefficients of power series $Bl(x)$		$Bl(x) > 0$ for $x_{min} < x < x_{max}$ x_{min} - minimal simulated displacement x_{max} - maximal simulated displacement			
Coefficients of power series $K_{ms}(x)$		$K_{ms}(x) > 0$ for $x_{min} < x < x_{max}$			
Coefficients of power series $L_e(x)$		$L_e(x) > 0$ for $x_{min} < x < x_{max}$			
Coefficients of power series $R_2(x)$, $R_3(x)$		$R_2(x)$, $R_3(x) > 0$ for $x_{min} < x < x_{max}$			
Coefficients of power series $L_e(x)$, $L_3(x)$		$L_e(x)$, $L_3(x) > 0$ for $x_{min} < x < x_{max}$			
Area of diaphragm	S_d	0.1			cm^2
Material of voice coil wire	copper or aluminum				

System Parameters

Enclosure type	driver in baffle, closed box, vented box , passive radiator, bandpass				
	Symb ol	Min	Typ	Max	Unit
Volume of air in enclosure	V_b	0.01			dm³ (l)
Volume of the rear enclosure	V_r	0.01			dm³ (l)
Area of port	S_p	> 0			cm^2
Acoustic mass of air moved in vent	M_{ap}	> 0			N/m^5
Acoustic resistance of enclosure losses due to leakage	R_{al}	> 0			kNs/m^5
Port resonance frequency	f_b	1		1000	Hz
Loss factor of the acoustical system at f_b considering vent losses	Q_p	0.01			
Loss factor of the acoustical system at f_b considering leakage losses	Q_l	0.01			
Acoustic resistance of vent losses	R_{ap}	> 0			kNs/m^5
Mechanical resistance of passive radiator suspension losses	R_{mp}	> 0			kNs/m
Stiffness of passive radiator suspension	K_{mp}	> 0			N/mm
Coefficients of power series $R_{ap}(v_p)$		$R_{ap}(v_p) > 0$ for $v_{p\ min} < x < v_{p\ max}$ $v_{p\ min}$ - minimal simulated velocity of air in port $v_{p\ max}$ - maximal simulated velocity of air in port			
Coefficients of power series $R_{mp}(v_p)$		$R_{mp}(v_p) > 0$ for $v_{p\ min} < x < v_{p\ max}$ $v_{p\ min}$ - minimal simulated velocity of air in port $v_{p\ max}$ - maximal simulated velocity of air in port			
Coefficients of power series $K_{mp}(v_p)$		$K_{mp}(v_p) > 0$ for $x_{p\ min} < x_p < x_{p\ max}$ $x_{p\ min}$ - minimal simulated passive radiator displacement $x_{p\ max}$ - maximal simulated passive radiator displacement			

Model for cone, radiation, room (Options)	- Piston, 2π-radiation, anechoic room - Piston, 4π-radiation, anechoic room - Import of frequency response of overall system				
Distance between diaphragm and listening position	*Distance*	0.001			m

Thermal Model					
Thermal Parameters	Symbol	Min	Typ	Max	Unit
Thermal resistance of path from coil to pole tips and magnet surface	R_{tv}	0.001			K/W
Thermal resistance of path from magnet to ambient air	R_{tm}	0.001			K/W
Thermal resistance of path from pole tips to magnet and frame	R_{tg}	0.001			K/W
Convection cooling parameter considering the effect of cone displacement	r_x	> 0		1000	W/Kmm
Convection cooling parameter describing the dependence of R_{tc} from cone velocity	r_v	> 0		1000	Ws/Km
Convection cooling parameter describing the dependence of R_{tt} from cone velocity	r_b	> 0		1000	Ws/Km
Factor describing the distribution of heat caused by eddy currents on voice coil and magnet	α	> 0			
Modes for simulating the voice coil, pole tip and magnet temperature (Options)	- Short term (voice coil hot; magnet and pole tips cold) - Long term (voice coil, magnet and pole tips hot)				

For certain combinations of model parameter values the model will become very stiff. This is particular true for large voice coil displacements. Although a special solver for stiff models is implemented the simulation may fail for very stiff models. Note that any numerical simulation algorithm may fail to converge. Normally a divergence can easily be detected as meaningless results are produced.

Stimulus					
	Symbol	Min	Typ	Max	Unit
Spectral Analysis					
sample frequency	f_s		*48*		*kHz*
resolution	Δf		*1.46*		*Hz*
order of distortion analysis	*n*	*2*		*32*	
Excitation tone					
frequency of first tone	f_1	*1.46*		*24000/n*	*Hz*
frequency of second tone					
constant frequency	f_2	*1.46*		1)	*Hz*
constant difference	$f_1 - f_2 = d$	*1.46*		2)	*Hz*
constant ratio	$f_1 / f_2 = r$	3)	*5.5*	3)	
voltage first tone 4)	U_1	*0*		*300*	*V*
voltage ratio between tones	U_2 / U_1	*-1000*	*0*	*20 lg(300V/U₁)*	*dB*
Frequency sweep					
steps		*1*	*10*	*200*	
start value of frequency sweep f_1	f_{start}	*1.46*		f_{end}	*Hz*
final value of frequency sweep f_1	f_{end}	f_{start}		*24/n*	*kHz*
Voltage sweep					
steps		*1*	*10*	*200*	

start value of voltage sweep U_1 [4]	U_{start}	0	0.5	U_{end}	V
final value of voltage sweep U_2 [4]	U_{end}	U_{start}		300	V
[1] $f_1 + (n-1)\, f_2 < 24$ kHz					
[2] $f_1 + (n-1)\, (f_1 - d) < 24$ kHz					
[3] $f_1 + (n-1)\, (f_1/r) < 24$ kHz					
[4] @ $U_2/U_1 = 1$					

Simulation

Initial Conditions

	Symbol	Min	Typ	Max	Unit
Initial displacement of the voice coil	$x(t=0)$	0		100	mm

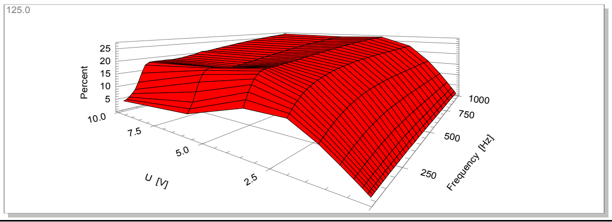
Solver

Fast solver	Solver without step size control
Precise solver	Solver with step size control

Application

Distortion

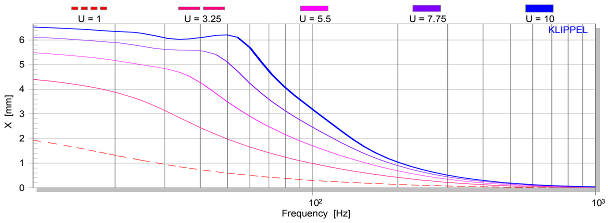
Nonlinearities of the speaker generate additional spectral components in the output signal. The harmonic distortions are not sufficient to describe the large signal behavior adequately. A fixed tone at resonance frequency f_s (representing a bass) component and a second tone f_1 varied over the audio band (representing a voice) produce audible summed-tone and difference-tone intermodulation in the pass-band. Whereas the measurement of relevant distortion components is time consuming the prediction of distortion components can be performed by your computer as a background task.



The picture above shows the second-order intermodulation distortion generated by a first tone with variable frequency f_1 and voltage U_1 and a second tone fixed at $f_2=28$ Hz.

Maximal Output

In the large signal domain there is no linear relationship between input and output amplitude. Thermal and nonlinear mechanisms limit the maximal output of the driver. Using SIM the maximal output can be assessed without risking to damaging the prototype.



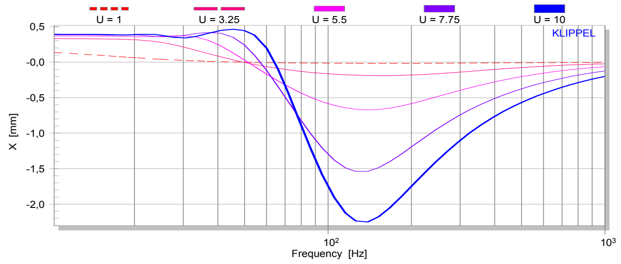
The picture above shows the amplitude compression of the voice coil displacement versus frequency.

Dominant Nonlinearity

Performing direct large signal measurements on real transducers shows the total effect of all thermal and nonlinear driver parameters. There are interactions between the nonlinear mechanisms that make it difficult to understand the relationship between physical cause (parameter) and observed effect in the output signal (distortion). Using SIM the effect of each nonlinearity can be investigated separately by setting all the other nonlinear parameters to zero. This way the dominant nonlinearities can be detected which limits the output and cause excessive distortion.

Coil jump out effect

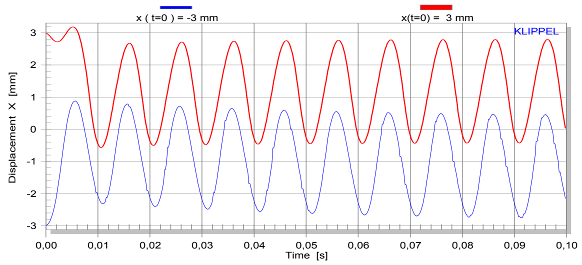
A driver with asymmetrical nonlinearities rectifies an AC-input and will generate a DC-component in the displacement dynamically. This DC-component will change the instantaneous working point and causes complicated interaction between all nonlinear mechanisms. For example an asymmetric stiffness characteristic may push the coil away from the optimal gap position. Above the resonance the Bl-nonlinearity may produce DC-components in the magnitude of the fundamental component. This reduces the maximal output amplitude and the efficiency and causes excessive distortion as well.



DC component in the voice coil generated dynamically by a sinusoidal tone

Stability

In the large signal domain the driver's response is not unique for the same steady-state excitation. Motor and suspension nonlinearities may produce multiple equilibrium solutions depending on the initial conditions. For example a symmetrical motor coupled with a soft suspension is instable at the rest position for frequencies above the resonance. A small disturbance will initiate a bifurcation into two states and the coil will be pushed out of the gap generating a high positive or negative DC-displacement dynamically. The simulation reveals an instability, its cause and effective ways to fight it.



Influence of initial displacement x(t=0) on steady-state response.

Thermal Power Compression

The heating of the voice coil will reduce the acoustical output (thermal power compression) and may also damage the speaker. The thermal parameters are the basis for predicting the instantaneous or final voice coil temperature for different scenarios.

Design Choices

The user may use the parameter editor to modify the nonlinear characteristics in order to investigate the performance of a virtual driver before the first prototype is finished.

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