Higher Modal Analysis - HMA (Pre-Release) S60

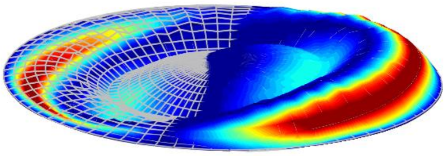
Specification to the KLIPPEL ANALYZER SYSTEM (Document Revision 1.3)

PRELIMINARY SPECIFICATION – PRODUCT IS STILL AWAITING FORMAL RELEASE

This specification is preliminary and is subject to change.

FEATURES

- Automatic Modal Analysis for transducers
- Decomposes vibration into separate modes
- Extracts modal parameters (e. g. damping)
- Displays material deformation (~stress)



BENEFITS

- Study characteristic vibration patterns individually and regarding their interaction
- Analyze measured and simulated data in the exact same way (=modal representation)
- Validate FEA simulation results
- Find sources of nonlinear distortion
- Solve sound radiation problems
- Improve cone geometry design

DESCRIPTION

Modal analysis is an optimal method for analysis of vibrating loudspeaker cones. The HMA decomposes the complex scanned vibration data into a set of second order resonators with associated mode-shapes (characteristic vibration-patterns). Studying the properties of these resonators (modal parameters) is highly valuable for the assessment of the mechano-acoustical performance. An even more detailed insight on how changes in these modal parameters influence the total response can be gained by studying the modal expansion, i. e. the identified set of transfer functions and mode shapes. The HMA allows including or excluding sets of modes from the accumulated expansion to study these effects. HMA is designed to integrate smoothly with measurements by the Klippel Vibration Scanning System (SCN). Data import from Polytec LDV devices or Finite Element software is possible through additional optional bridge-modules (POLY2SCN, FEM2SCN).

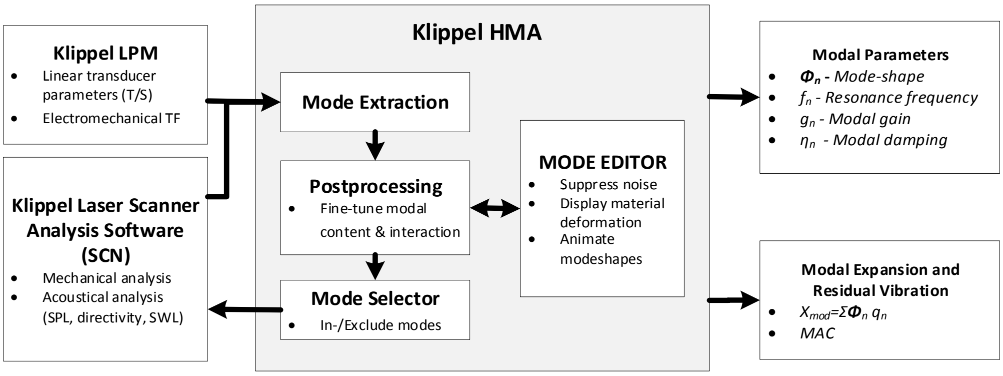
Article number	1001-111

CONTENT

1 Principle

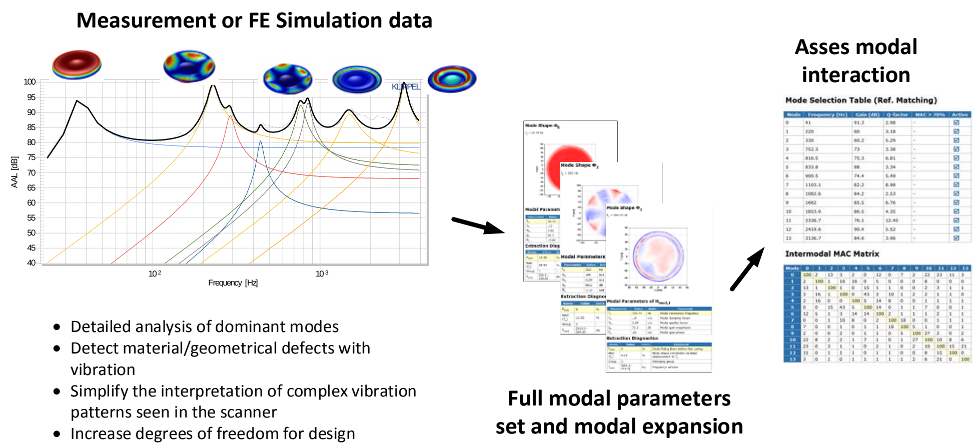
Objective

The HMA module is dedicated to automatic extraction of modal vibration information of loudspeaker transducer diaphragms. It works on round, ring-formed and rectangular shapes. It expects input of diaphragm vibration data from the Klippel Laser Vibration Scanner System SCN (or imported to its data-format from similar sources) along with a measurement of liner transducer parameters (Klippel LPM).



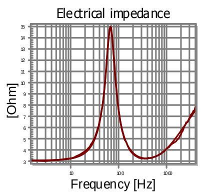
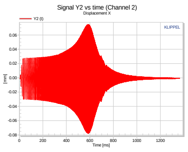
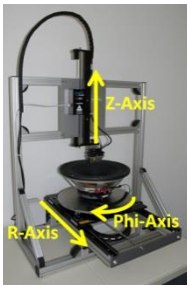
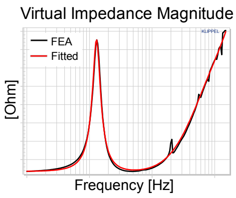
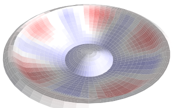
On the output side it provides a modal expansion, which consists of a sum of second order resonators with associated modal parameters q_n: Modeshapes ϕ_n (characteristic vibration pattern of each mode), resonance frequency f_n, gain g_n and damping η_n. Vibration components not included in the modal expansion will be lumped as "residual vibration". Orthogonality (independence) of the modes is assessed in percent (MAC-Intercorrelation matrix).

Functionality (Application)



Loudspeaker cone design and optimization requires a dedicated analysis tool for higher order modes (breakups). In order to quantify the changes of geometric or material modifications, accurate modal parameters need to be compared for different scenarios based on finite element simulations or measurements of prototypes. The HMA is developed specifically to provide the required input data to all this processes. In addition, the HMA computes the gradient of the displacement field which provides an animated 3D color-shade plot showing deformation of the material (which is proportional to material stress). This way, cone regions with high deformation (potential candidates for producing substantial nonlinear distortion) can be identified.

2 Components of the HMA Module

2.1 HMA analysis (minimum requirement, measurements externally provided)			Spec#
HMA Software	Measurement module for conducting Higher Order Modal Analysis		S60
SCN Laser Scanning Vibrometer Analysis Software	Analysis software for vibrometric laser data		C5 (2510-010)
2.2 Additional components for self-performed measurements			Spec#
Measurement device		Klippel Analyzer 3 (alternatively Distortion Analyzer 2) is the hardware platform for the measurement modules performing the generation, acquisition and digital signal processing in real time.	H1 H3
LPM – Module		Module to identify the electrical and mechanical parameters of electro-dynamical transducers by measuring the voltage and current at the speaker terminals.	S2
TRF - Module		The Transfer function (TRF) is a dedicated PC software module for measurement of the transfer behavior of a loudspeaker.	S7
Laser Scanning Vibrometer Hardware (SCN)		The Scanning Vibrometer (SCN) performs a non-contact measurement of the mechanical vibration and the geometry data of cones, diaphragms, panels and enclosures.	C5 (2510-004)
2.3 Alternative ways to gather SCN/LPM data – 2SCN bridge product family			Spec#
FEM2SCN Module		Module to identify the electrical and mechanical parameters of electro-dynamical transducers from finite element simulations in COMSOL and PAFEC and for importing surface vibration data to Klippel SCN format.	Contact sales
POLY2SCN Module		Module for importing surface vibration data to Klippel SCN format.	S45

3 Higher Order Modal Analysis

3.1 Principle

Principle

The electromechanical transfer function (voltage displacement) H_x measured at each scanning point, is transformed into the pure mechanical transfer function $H_{x/F}$ via the Bl factor and the electrical impedance of the transducer.

$$H_{X/F}(\omega) = H_X(\omega)\frac{Ze(\omega)}{Bl}$$

The HMA assumes that the vibration field measured on the transducer surface $X(\mathbf{r},\omega)$, can be represented by the superposition of the dominant modes.

$$X(\mathbf{r},\omega) = \sum_{n=1}^{\infty} \boldsymbol{\varphi}_n(\mathbf{r}) q_n(\omega)$$

At each point $\mathbf{r}$ on the surface the displacement is the product of the mode shape $\boldsymbol{\varphi}_n(\mathbf{r})$ and $q_n(\omega)$ the modal resonator

$$q_n(\omega) = \frac{g_n}{\omega_n^2 - \omega^2 + j\eta_n\omega_n^2}$$

described by the following parameters, ω_n the resonance frequency, η_n the modal damping factor and g_n the modal complex gain.
The goal of the HMA module is to extract the modal parameters and the mode shapes of the loudspeaker by means of an automatic frequency windowing, singular value decomposition and circle fitting processes.

3.2 Analysis Process

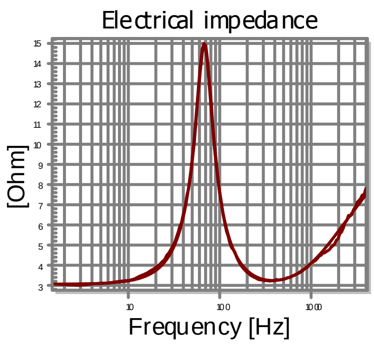
Vibrometer Scan

A detailed scanner data with enough frequency and spatial resolution is required for accurate modal parameter extraction.

TRF Setup: HMA needs precise information in the lower frequency range. Therefore the following Settings have to be considered.

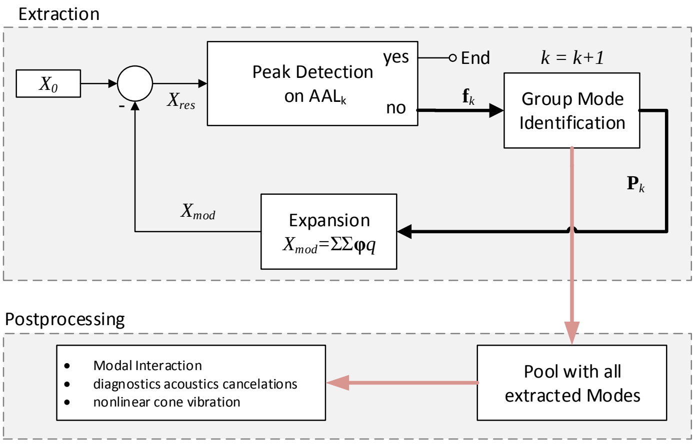
- The **frequency range** should conceal a frequency range from **10 Hz to 10000 Hz**, for micro speakers a scan should at least start at 100 Hz.
- **Resolution**: 5.86 Hz or lower
- **Averages**: 4 or more, depending on the signal to noise ratio (optical acces to diaphragm). More can be required for microspeakers placed under screened cases
- **Shaping**: 6-9 dB/oct. for sufficient SNR on the voice coil displacement at high frequencies.
- **Postprocessing Settings:** smoothing and log-reduce to: 60 points/oct.

LPM Measurement



Lumped parameter model
For identification of the piston mode vibration of the loudspeaker the linear parameters are required.
The Thiele small parameters measured with the LPM module provide the **mechanical information** of the piston mode and the characteristics of the electrodynamic **motor**

Modal Extraction



The HMA analyses the Accumulated Acceleration Level $AAL(\omega)$ on the driver surface and extract the dominant modes as prominent peaks. Once this process is finished, the modal displacement is synthetized and subtracted from the measured displacement producing the residual vibration to be used in the new extraction.

The initial group $k=0$ takes the total measured displacement X_0 which is used to compute the AAL and to find the dominant peaks stored at the resonance frequencies $\mathbf{f}_k$ which are the inputs of the Group Mode Identification which computes the modal parameter vector $\mathbf{P}_K=[\mathbf{f}_n , \boldsymbol{\eta}_n , \mathbf{g}_n , \boldsymbol{\varphi}_n]^T$. This vector comprises the resonance frequencies $\mathbf{f}_n$, damping factors $\boldsymbol{\eta}_n$, complex gains $\mathbf{g}_n$ and mode shapes $\boldsymbol{\varphi}_n$ of the n^{th} extracted modes of the group. The extracted parameters are used to synthesize the modal displacement X_{mod} by the superposition of the $n=1,2,\ldots,N_{dom}$ modes of the different groups $k=1,2,\ldots,K_L$. This process is repeated according to the number of groups selected by the user.

Postprocessing and link with SCN software

The HMA includes different tools to analyze the extracted modes. Acoustic cancellations and directivity are symptoms of a non-proper interaction of the structural modes. This process can be significantly simplified and clarified by investigating the effect of the superposition of few dominant modes. This can be easily done with the Mode Selection Table that is presented after the extraction.

In order to improve the quality of the extracted modes, the HMA editor provides a powerful technique based on Zernike transform to suppress the noise of the experimental data, which is functional for round speaker shapes. It also provides the regions of the cone exhibiting large material deformations causing nonlinear distortion on the acoustic pressure.

4 Input parameters (setup)

4.1 Input

	Parameter Name	Parameter type	Description
Input Parameters	LPM	Link	Loudspeaker motor and Mechanical transfer function determine the piston mode of the model *Re* : Electrical Resistance *Le* : Voice coil Inductance *L2* : Para-Inductance of the voice coil *R2* : Electrical resitance due to eddy currents *Bl* : Force factor (Bl product) M_{ms} : Mechanical mass K_{ms} : Mechanical stiffness of the suspension R_{ms} : Mechanical resistance λ : Suspension creep factor
Input Files	Exported SCN file*.sce in SCN data-container	Link	Exported Klippel Scanner interpolated vibration/geometry data in ASCII file format (.sce). See SCN manual for details. During the setup process, this file will be loaded into an SCN data container operation stored in a dBLab database.
Input Variables	Diaphragm shape	Check box	Select the entire diaphragm, ideally including a small portion of the surrounding rigid enclosure: - Circular - Rectangular - Ring (coaxial units)
Input values	Diaphragm dimension	Input Value	Determine the size of the diaphragm - Radius (*r*): Circular - Rectangular (*l*,*w*): length and width - Ring, Internal and external Radius: r_i and r_e
	High pass frequency	Input Value	Avoid HMA to extract low frequency peaks (artifacts) as valid modes.
	Window Peak	Input Value	Value in dB used to determine the lower and upper frequencies of the window. Limit where the amplitude of the AAL curve decays this value at both sides of the resonance frequency.
	Modes per Group	Input Value	Maximum number of modes attempted to be extracted on each group
	Total Groups	Input Value	Total number of groups to be extracted
	Fine tuning Method	Select list	Selection between two methods - AAL based - Full complex displacement over surface

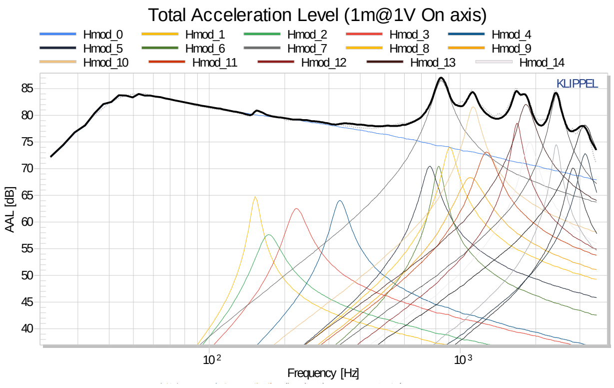
5 Measurement Results

5.1 Results

Output Curves

<u>Total Acceleration Level (1m@1V On Axis)</u>

AAL of the measured data and the modal expansion with each resonator. Frequency response curves of the identified modes and the superposition of the user enabled modes.



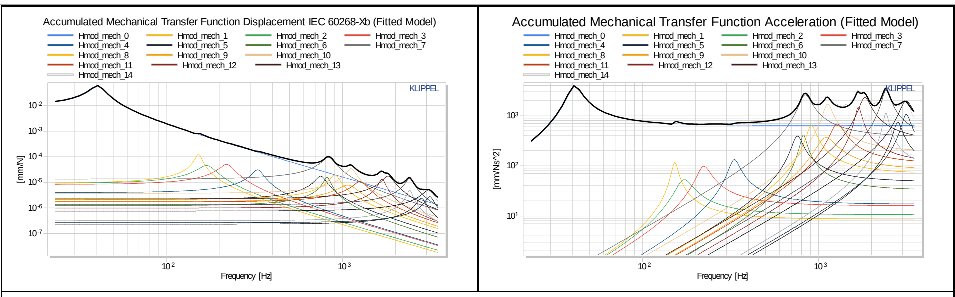
Acumuated acceleration level of the measured data and the modal expansion

How to interpret the AAL chart

The Klippel magnitude AAL (see Scanner software AN-31 and AN-32) is used to describe the mechanical energy of the cone. The superposition (as a complex displacement) of the different identified modes should provide a similar AAL than the measured data. The dominancy of different components, the modal density, damping properties and the modal interaction are easily evidenced in this chart. The second order resonators are transformed in the electromechanical domain using the Bl factor and the electrical impedance. This figure is updated if the “Mode Selection Table” is modified or if the mode is updated with the HMA Editor.

<u>Accumulated Mechanical Transfer Function IEC60268</u>

This plot shows the mechanical transfer functions and the complete expansion according to the Standard integrated on the cone surface using the respective mode shape. The second order resonators defined by the modal parameters are displayed with different colors since they are in the mechnical domain, the electrical effects are removed.



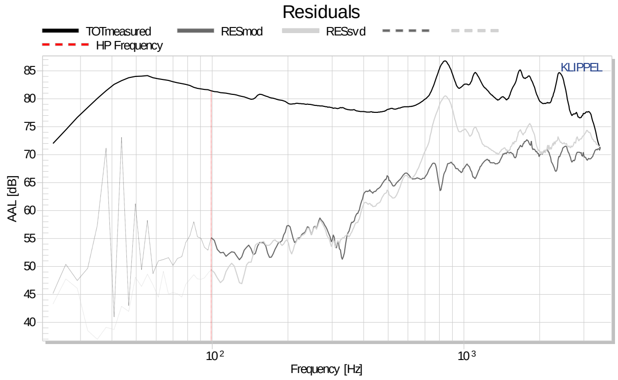
AAL_{RES} of the residual displacement

How to interpret the Accumulated Mechanical Transfer Function chart:

This data is presented in the mechanical domain meaning that the electrical damping and the inductance effects are removed. It shows the fitted resonators and the complete expansion corresponding to the structural vibration of the cone. When changing the Mechanical transfer Function parameter from Displacement IEC60268 to Acceleration, the fitting quality of the modal parameters become more clear. *This figure is updated if the “Mode Selection Table” is modified or if the mode is updated with the HMA Editor.*

AAL of the residual vibration

Plot of the AAL of the residual vibration after subtracting the modal expansion model from the measured data.

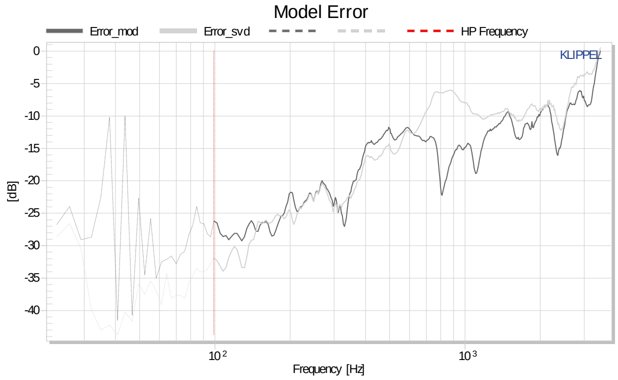


Residual

Note: If some distinct peaks can be recognized in the residual curve RES_{mod} means that few modes more can be extracted in a new group. *This figure is updated if the "Mode Selection Table" is modified or if the mode is updated with the HMA Editor.*

Error between the model and the measurement

To evaluate the accuracy of the modal expansion model, the error in the magnitude and phase of the displacement over the radiator surface is shown.



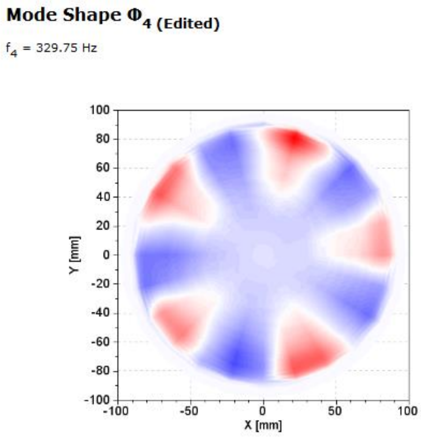
Modal Errors

Note: A deviation error of 100% between the model and the experiment is 0 dB.

Output Windows

Mode Shape and resonator parameters

Graphical representation of the mode shape with the same Klippel SCN color scale. Table with the complete modal parameters and relevant extraction diagnostics information.



Modal Parameters of $H_{mod\_mech,4}$

Parameter	Value	Units	Comment
f_n	329.75	Hz	Modal resonance frequency
η_n	.06	n/a	Modal damping factor
Q_n	7.7	n/a	Modal quality factor
g_n	-34.88	dB	Modal gain magnitude
θ_n	-2.22	rad	Modal gain phase

Extraction Diagnostics

Name	Value	Units	Comment
E_{SVD}	37.5	%	Circle fitting Error before fine tuning
$MAC(f_n)$	10.28	%	Mode shape correlation on total displac f_n
Group	3	-	Belonging group
f_{wind}	[307.6 - 351.6]	Hz	Frequency window

Mode shape and resonator parameters plot and table

Output Parameters

Mode Selection table

Summary of all the extracted modes. This table allows the user to activate and deactivate different modes to be included in the expansion.

Mode Selection Table (Ref. Matching)

Mode	Frequency (Hz)	Gain (dB)	Q-factor	MAC > 70%	Active
0	127	133.5	3.14	-	☑
1	2000.4	132.4	11.41	-	☑
2	5632.5	131.2	10.65	-	☑
3	8174.2	127.6	13.2	-	☑
4	11063	125.8	12.78	-	☑
5	13192.1	129.4	10.24	-	☑

Intermodal MAC Matrix (%)

Mode	0	1	2	3	4	5
0	100	0	0	1	0	5
1	0	100	0	1	0	2
2	0	0	100	3	1	5
3	1	1	3	100	0	2
4	0	0	1	0	100	19
5	5	2	5	2	19	100

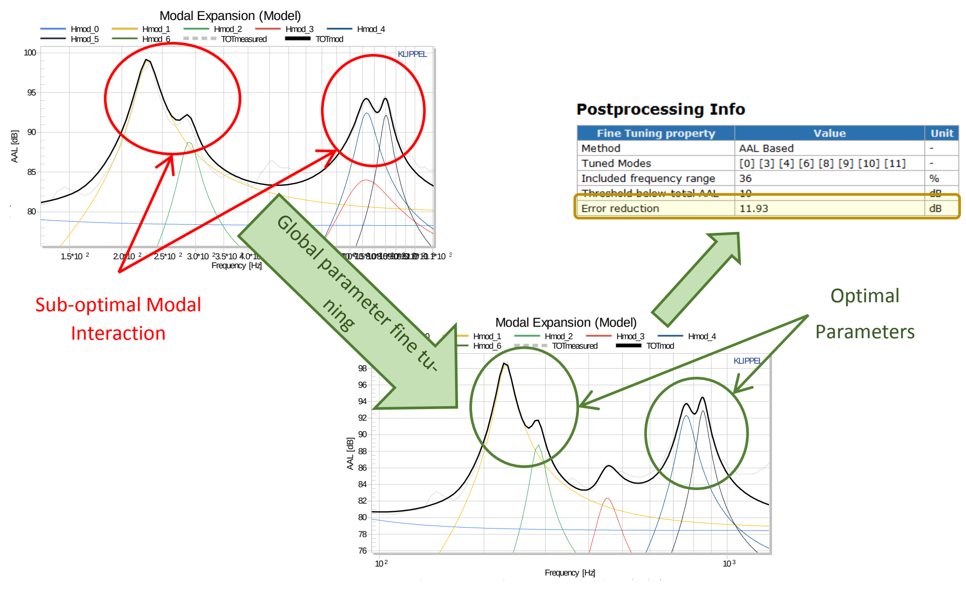
Mode Selection Table and Intermodal MAC Matrix

Note: The Intermodal MAC matrix shows the degree of correlation between the modes in %.

Postprocessing options

<u>Global Fine tuning of Parameters</u>

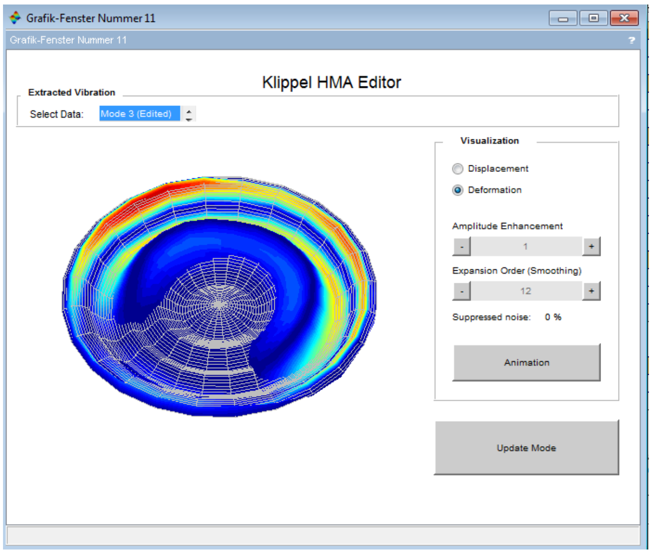
Extracted Modal Parameters are optimized based on the superposition to cope with the interaction of the neighboring modes. Two different approaches of fine tuning methodes can be selected in the HMA.



<u>HMA Mode Editor</u>

Graphical User Interface use to investigate the mode shapes, improving the data analysis using advanced image processing transformations.

Computation of the material deformation on the surface.



Export Files

Measured data	**.sce Klippel Scanner file containing the mechanical (transformed with the Bl and the electrical impedance) response of the driver*
Modal Expansion	**.sce Klippel Scanner file containing the synthetized displacement based on the modal expansion*
Modal Residual	**.sce Klippel Scanner file containing the residual displacement after reducing the modal expansion from the measured data*

6 Application/Diagnostics

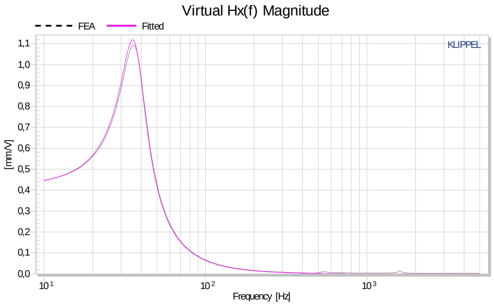
6.1 Modal analysis based on FE Simulation

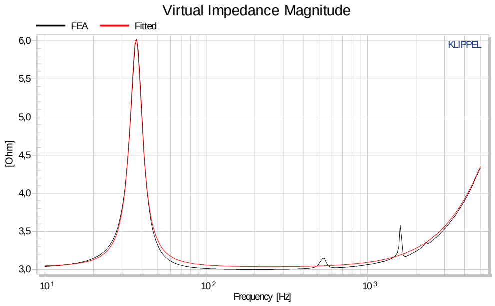
FE Model and the solution

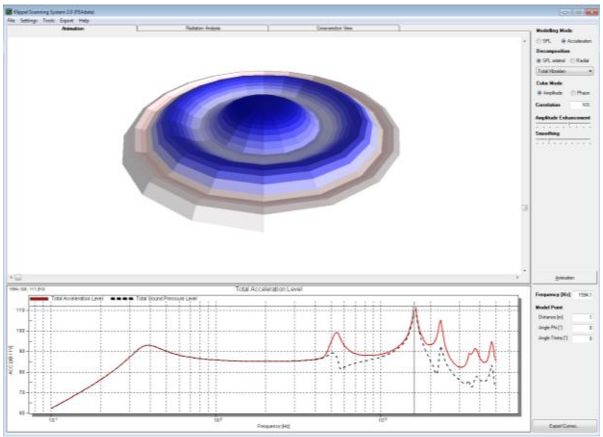
A Finite Element (FE) simulation is the best way to start a design process or to improve existing loudspeaker prototypes. A reliable and precise finite element model requires accurate geometry information and the effective material parameters of the transducer. These parameters usually measured by structural tests on samples of the different components do not describe the effects due to coupling, gluing and others related to the assembling of the complete unit. In order to estimate this effective parameters, a system identification based on laser scanning and modal updating of the complete transducer is required and can be achieved by minimizing the error between the modal parameters extracted with the HMA module used for the FE model and the first built prototype.
To illustrate the process, the modal parameters of a FE model will be extracted.
The example model consists of a conical loudspeaker (modelled with shell elements) with a voice coil force applied on the base of the voice coil former. The study is done from 10 Hz to 5 kHz.

Virtual LPM and scanner

Transferring the FE data to the Klippel SCN software is done by using the **FEM2SCN** module (which is separately available, see section 2.3). It provides the equivalent Thiele-Small parameters and the *.sce scanner file required to perform HMA. This module includes a virtual LPM operation that extracts the TS parameters by fitting the simulated displacement/voltage transfer function and the electrical impedance.



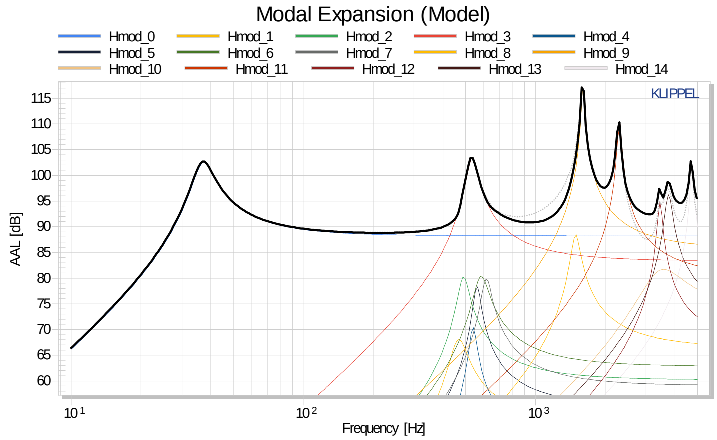




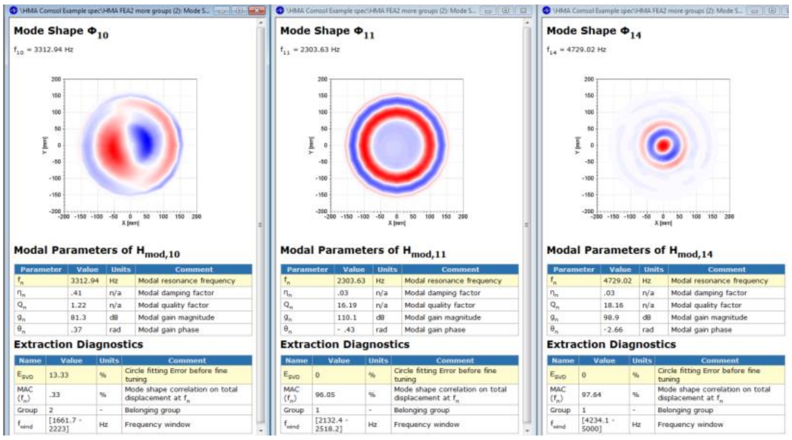
The scanner data should be checked to guarantee that no interpolation errors occurred.

HMA of FE model

The generated SCN file and the TS parameters can be used with the HMA module in the same way as if the transducer was measured with a laser vibrometer.



The modal parameters corresponding to all the identified resonators and mode shapes presents in the FE element simulation are shown and can be analysed as usual.

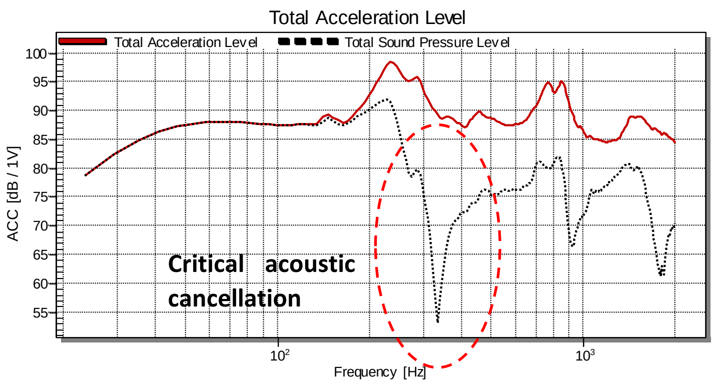


Note that the extracted modal parameters are the base for the identification of the effective material parameters using the optional Klippel module MPI (material parameter identification).

6.2 Diagnostics on critical Acoustic Cancellation on the band pass

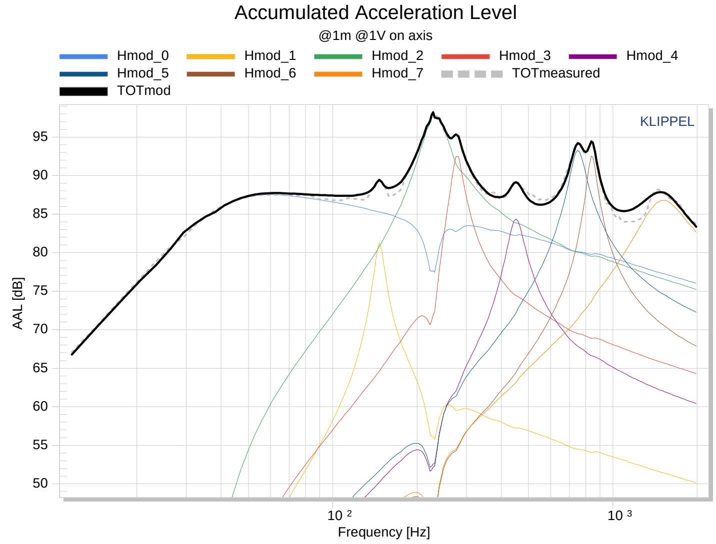
Vibration Measurement

The following midrange driver exhibits a critical acoustic cancellation >30 dB SPL at 350 Hz. In order to determine the root cause of the problem and to fix such a design, a detailed investigation of the higher order modes and the interaction between them is required.



HMA Results for the dominant modes found

Using the HMA module, the following dominant modes are found. More modes with lower energy can be extracted by increasing the numbers of groups to find the modes. In this case the cancellation effect is clearly an affect produced by dominant modes.

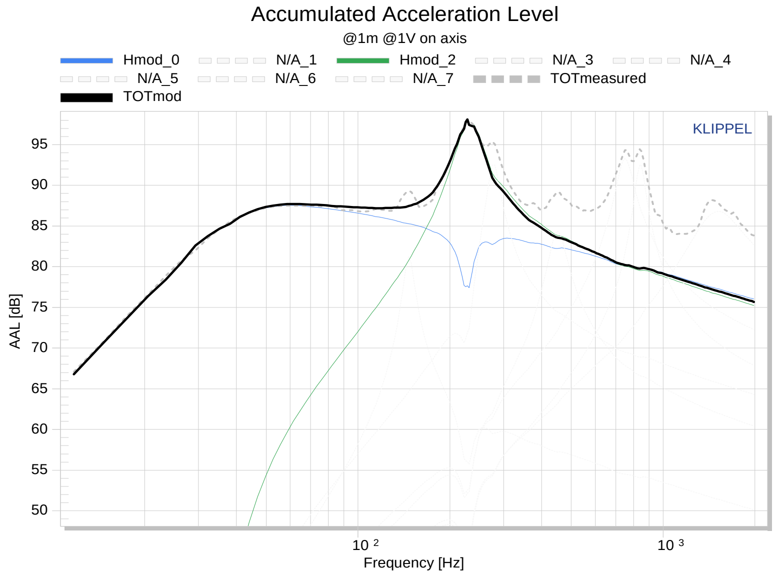


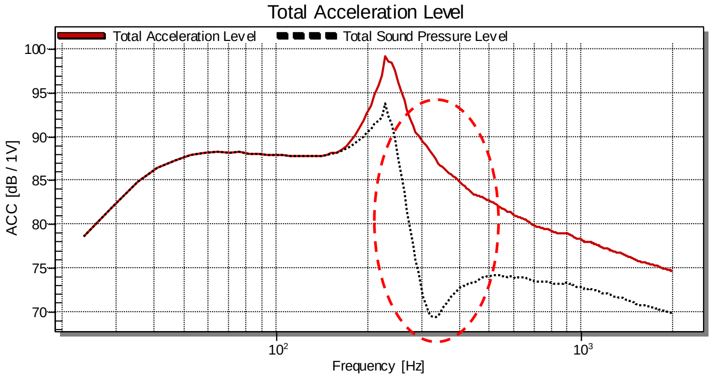
Selecting only two modes

To simplify the analysis, only two of them are retained in the expansion. This can be done by selecting only the two modes from the selection list.

Mode Selection Table (Ref. Matching)

Mode	Frequency (Hz)	Gain (dB)	Q-factor	MAC > 70%	Active
0	35.6	118.4	6.25	-	☑
1	146.4	92	13.22	-	☐
2	227.4	117.4	11.88	-	☑
3	276.8	107.4	12.54	-	☐
4	447.7	102.6	8.07	-	☐
5	745.5	113.3	8.12	-	☐
6	839.6	109.3	13.66	-	☐
7	1434.8	119.1	2.5	-	☐



Diagnostics Results	By exporting the modal expansion including only the two selected modes to the Klippel Scanner software, it is possible to reconstruct the SPL response of the interaction between the modes.  Cancellation at 350 Hz is due to the interaction between the piston and the first breakup modes The cancellation appears at 350 Hz. The root cause of this particular problem is a destructive interference produced by an excess of energy of the first breakup mode which resonance frequency is 230 Hz and the piston mode. Note that the cancellation appears at 350 Hz just when the phase of the breakup rotates 180 degree after the resonance increasing the amount of antiphase vibration.

Find explanations for symbols at:
http://www.klippel.de/know-how/literature.html
Last updated: June 07, 2019