Higher Modal Analysis - HMA (Pre-Release) S60

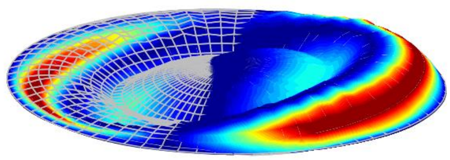
Specification to the KLIPPEL ANALYZER SYSTEM (Document Revision 1.3)

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)
- 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 is possible through additional optional bridge-modules (POLY2SCN).

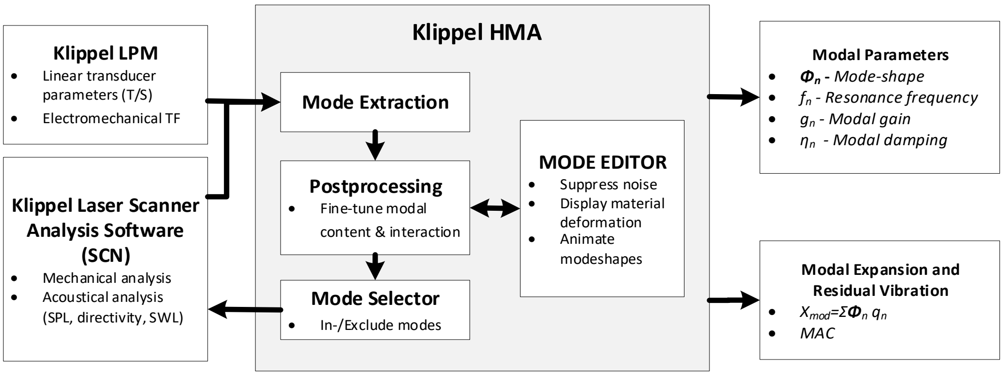
Article number	1001-111

CONTENT

1 Principle

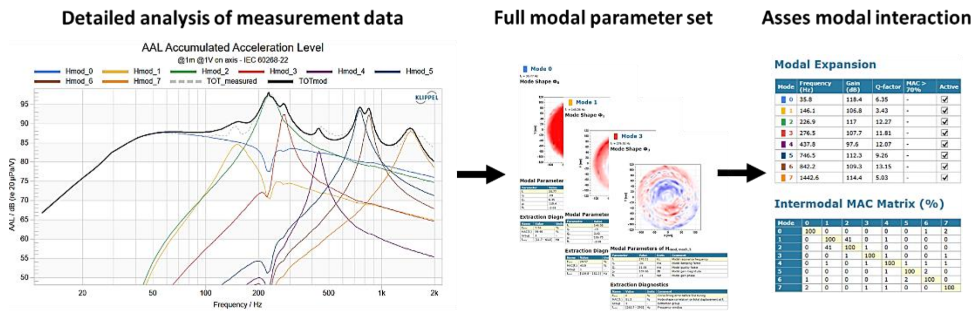
Objective

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).

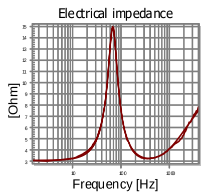
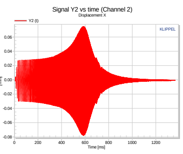
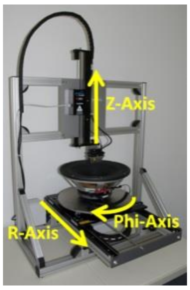
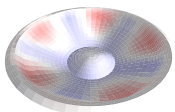
Functionality (Application)



- Detailed analysis of dominant modes
- Detect material/geometrical defects with vibration
- Simplify the interpretation of complex vibration patterns seen in the scanner
- Increase degrees of freedom for design

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#
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 $X(r,\omega)$, can be represented by the superposition of the dominant modes.

$$X(r,\omega) = \sum_{n=1}^{\infty} \varphi_n(r) q_n(\omega)$$

At each point $\mathbf{r}$ on the surface the displacement is the product of the mode shape $\varphi_n(r)$ 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

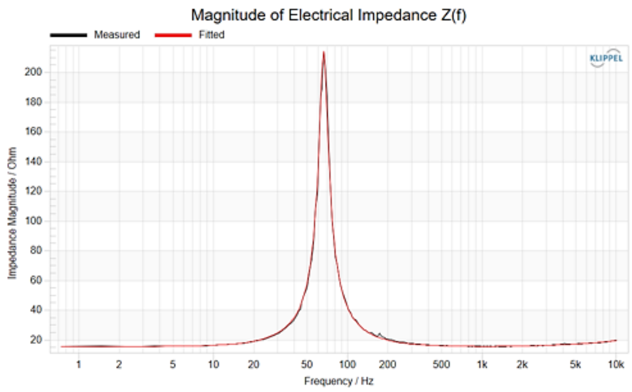
Vibrometer Scan

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 include all relevant resonances, especially the piston mode resonance with a margin of at least 1 octave. Usually a scanning range of 10 Hz to 10000 Hz (woofers), for micro speakers from 100 Hz is sufficient.
- **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

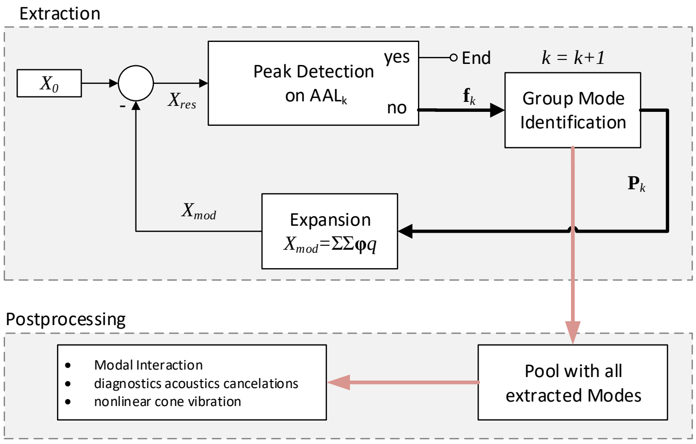


Lumped parameter model

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 $n=1,2,...,N_{dom}$ modes of the different groups $k=1,2,...,K_L$. 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 affected by the interaction of the structural modes. This process can be significantly simplified and clarified by investigating the effect of the superposition of few dominant modes. To study this, include and exclude modes from the modal expansion in the Mode Selection Table that is presented after the extraction. Afterwards, the result can be exported from HMA and the radiation effects analyzed in the SCN software.

In order to improve the quality of the extracted modes, the HMA editor provides a Zernike transform noise-suppression 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 model
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

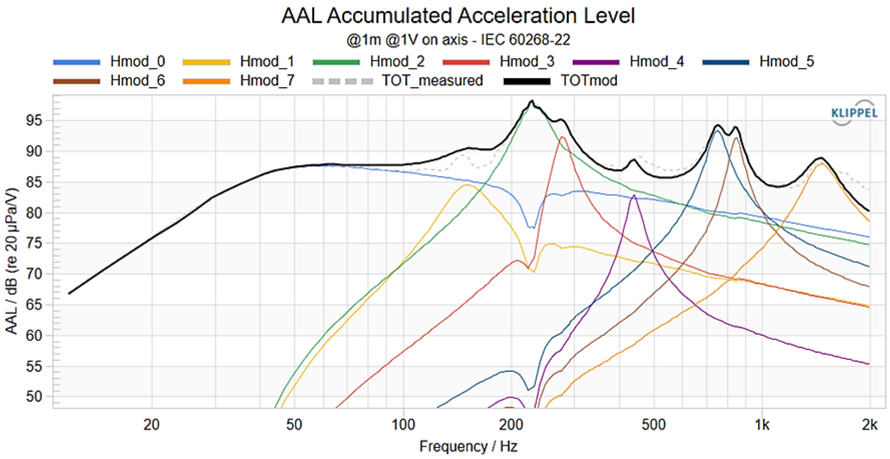
5 Measurement Results

5.1 Results

Output Curves

Total Acceleration Level (1m@1V On Axis)

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.



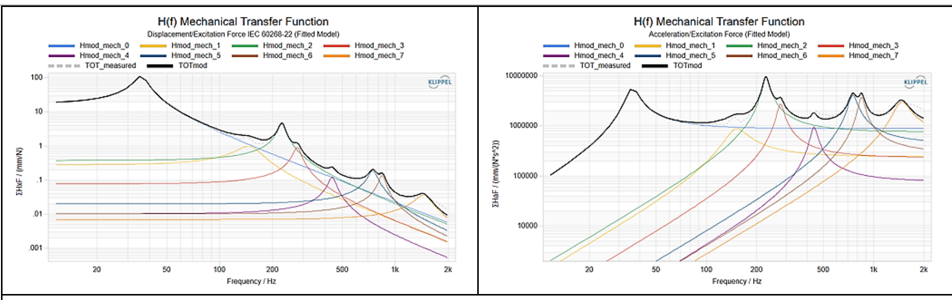
Acumuated acceleration level of the measured data and the modal expansion

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.

Accumulated Mechanical Transfer Function IEC60268

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.



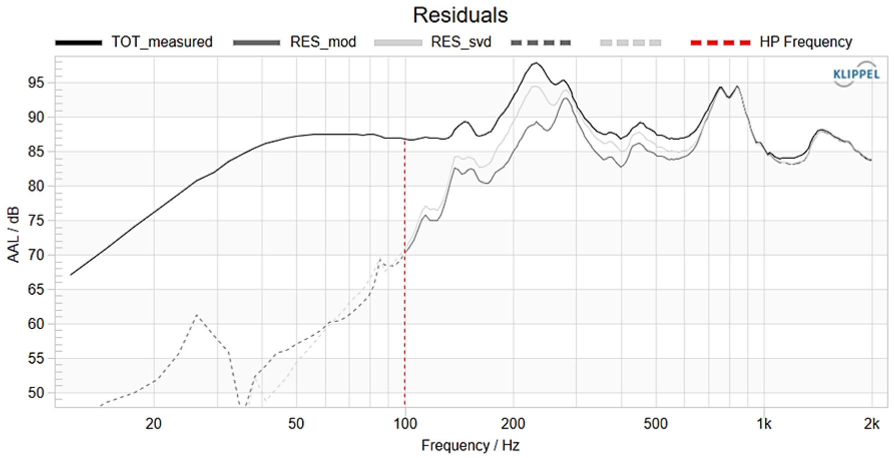
AAL_{RES} of the residual displacement

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.

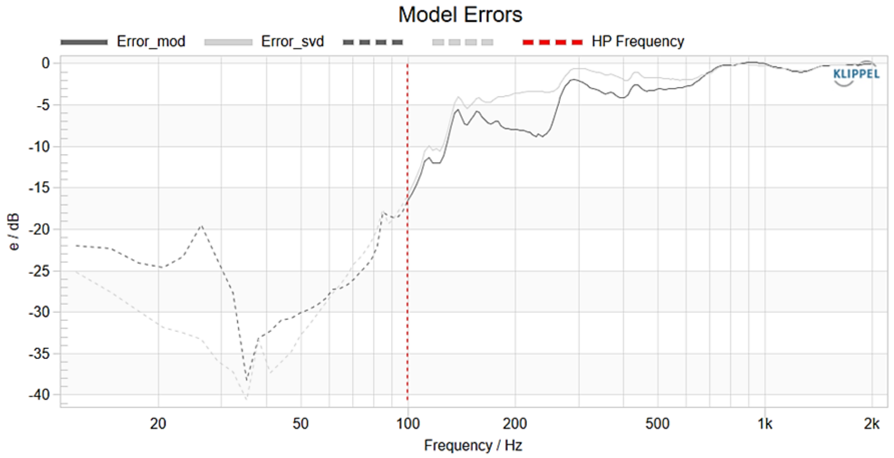


Residual

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.



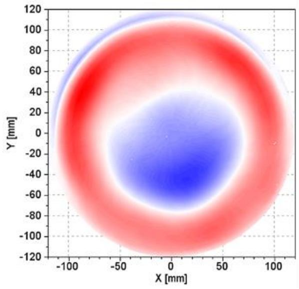
Modal Errors

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

Output Windows

<u>Mode Shape and resonator parameters</u>

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 $H_{mod,mech,2}$

Parameter	Value	Units	Comment
f_n	226.85	Hz	Modal resonance frequency
η_n	.04	n/a	Modal damping factor
Q_n	12.27	n/a	Modal quality factor
g_n	116.96	dB	Modal gain magnitude
θ_n	3.25	rad	Modal gain phase

Extraction Diagnostics

Name	Value	Units	Comment
E_{SVD}	25	%	Circle fitting error before fine tuning
MAC (f_n)	88.74	%	Mode shape correlation on total displacement at f_n
Group	1	-	Extraction group
f_{wind}	[216.8 - 240.2]	Hz	Frequency window

Mode shape and resonator parameters plot and table

Output Parameters

<u>Mode Selection table</u>

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

Modal Expansion

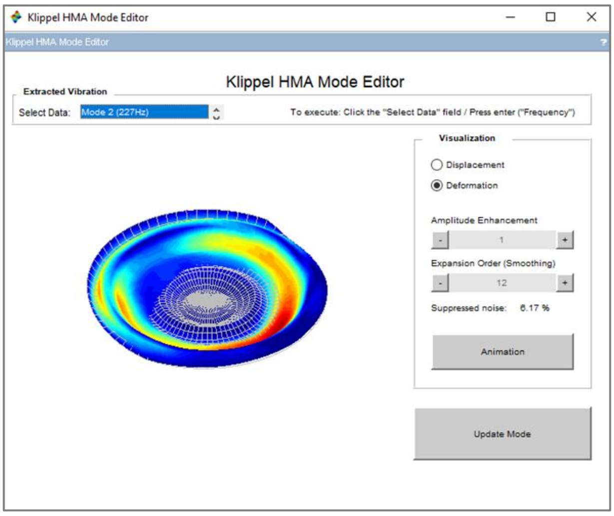
Mode	Frequency (Hz)	Gain (dB)	Q-factor	MAC > 70%	Active
0	35.8	118.4	6.35	-	☑
1	146.1	106.8	3.43	-	☑
2	226.9	117	12.27	-	☑
3	276.5	107.7	11.81	-	☑
4	437.8	97.6	12.07	-	☑
5	746.5	112.3	9.26	-	☑
6	842.2	109.3	13.15	-	☑
7	1442.6	114.4	5.03	-	☑

Intermodal MAC Matrix (%)

Mode	0	1	2	3	4	5	6	7
0	100	0	0	0	0	0	1	2
1	0	100	41	0	1	0	0	0
2	0	41	100	1	0	0	0	0
3	0	0	1	100	1	0	0	1
4	0	1	0	1	100	1	1	1
5	0	0	0	0	1	100	2	0
6	1	0	0	0	1	2	100	0
7	2	0	0	1	1	0	0	100

Mode Selection Table and Intermodal MAC Matrix

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

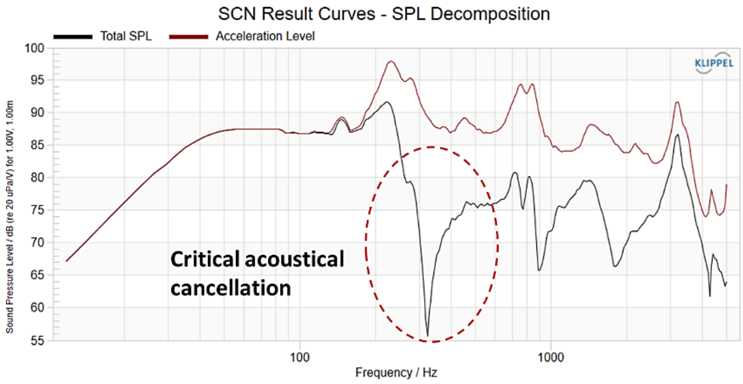
<table>
<tr><td rowspan="2">Postprocessing options</td><td colspan="2"><u>Global Fine tuning of Parameters</u>
Extracted Modal Parameters are optimized based on the superposition to cope with the interaction of the neighboring modes. The following wwo different approaches of fine tuning methodes can be selected in the HMA:
Full complex displacement
AAL based.</td></tr>
<tr><td colspan="2"><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.

</td></tr>
<tr><td rowspan="3">Export Files</td><td>Measured data</td><td>*.sce Klippel Scanner file containing the mechanical (transformed with the Bl and the electrical impedance) response of the driver</td></tr>
<tr><td>Modal Expansion</td><td>*.sce Klippel Scanner file containing the synthetized displacement based on the modal expansion</td></tr>
<tr><td>Modal Residual</td><td>*.sce Klippel Scanner file containing the residual displacement after reducing the modal expansion from the measured data</td></tr>
</table>

6 Application/Diagnostics

6.1 Diagnostics on critical Acoustic Cancellation on the band pass

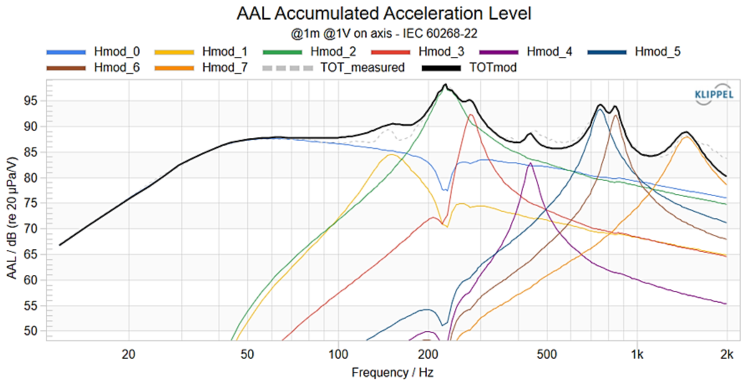
Vibration Measurement

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.

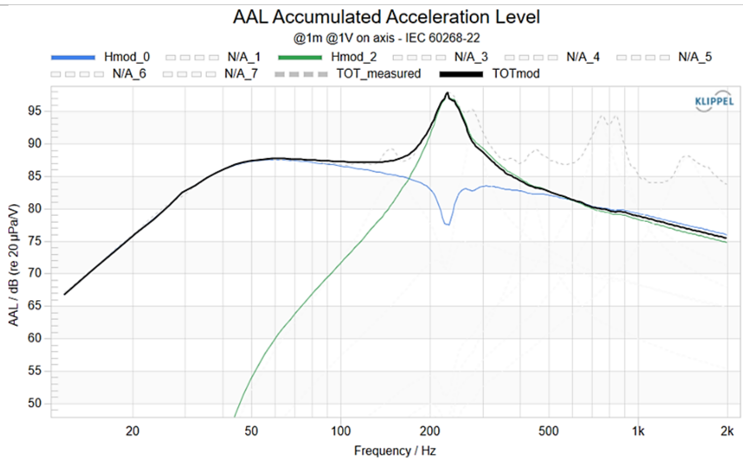
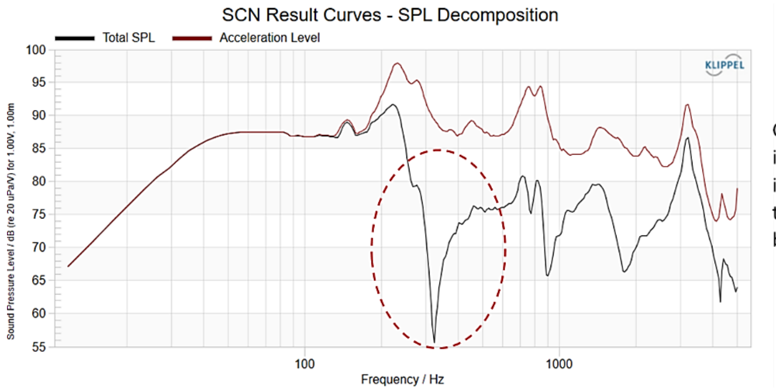


Selecting only two modes

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.

Modal Expansion

Mode	Frequency (Hz)	Gain (dB)	Q-factor	MAC > 70%	Active
0	35.8	118.4	6.35	-	☑
1	146.1	106.8	3.43	-	☐
2	226.9	117	12.27	-	☑
3	276.5	107.7	11.81	-	☐
4	437.8	97.6	12.07	-	☐
5	746.5	112.3	9.26	-	☐
6	842.2	109.3	13.15	-	☐
7	1442.6	114.4	5.03	-	☐

<table>
<tr><td></td><td>
</td></tr>
<tr><td>Diagnostics Results</td><td>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.</td></tr>
</table>

Find explanations for symbols at:
http://www.klippel.de/know-how/literature.html
Last updated: June 09, 2021