Cone Vibration and Radiation Diagnostics **AN 31**

Application Note to the KLIPPEL R&D SYSTEM

The laser scanning vibrometer provides the precise cone geometry and the cone vibration up to 25 kHz. This data shows the modes of the vibration and their contribution to the radiated sound pressure output in the 3D space.

This data is the basis for cone vibration and radiation analysis to reveal the physical causes for peaks and dips in the frequency response and to detect rocking modes and other irregularities which cause voice coil rubbing.

The application note is a step by step instruction for performing diagnostics. A flat speaker intended for woofer application is used as a practical example.

CONTENTS:

Terms and Definitions

Cone Scanning

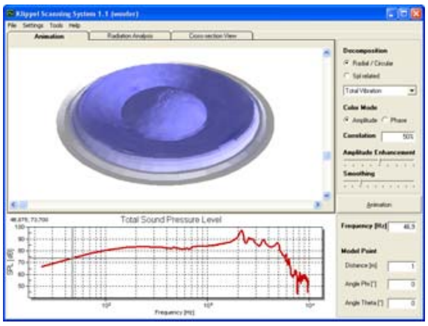
The Scanning Vibrometer (SCN) performs a non-contact measurement of the mechanical vibration and the geometry data of cones, diaphragms, panels and enclosures. One rotational and two linear actuators (φ, r, z) move a laser displacement sensor over a user-defined grid. At each measurement point the transducer is excited by a stimulus giving sufficient spectral resolution and high SNR in the measured response over the whole audio band (< 25 kHz). The scanner system comprises the Transfer Function module TRF, DA2, control box and a triangulation laser G32. The collected geometry data can be exported to other FEA/BEA applications while the vibration data can be analyzed within the SCN Analysis software.

KLIPPEL

Klippel GmbH
Mendelssohnallee 30
01309 Dresden, Germany

www.klippel.de
info@klippel.de

TEL: +49-351-251 35 35
FAX: +49-351-251 34 31

Analysis Software		Modern techniques of image processing are used for enhancing relevant information, suppressing noise and animating the vibration as a stroboscopic video. The sound pressure output in the far field and the directivity pattern are calculated and the contribution of each vibrating point on the vibrating surface is visualized. The software indicates critical vibration pattern and uses decomposition techniques for separating radial and circular modes.
Sound pressure level	$SPL(r_o) = 20\log\left(\frac{\lvert p(\omega)\rvert}{p_o}\right)$ with $p(\omega) = \frac{\omega^2\rho_0}{2\pi}\int_S \frac{x_n(r_i)}{\lvert r_o - r_i\rvert} e^{-jk\lvert r_o - r_i\rvert} dS_i$	Using the Rayleigh integral the sound pressure at the point r_o in the sound field is calculated by integrating the acceleration of each point r_i weighted by the area dS_i of each surface element and the distance between point r_i and the point r. Note the Rayleigh integral is a useful approximation for relatively flat geometries operated in an infinite baffle.
Acceleration Level	$L_a = 20\log\left(\frac{\omega^2\rho_0}{p_0 2\pi}\int_S \frac{\lvert x_n(r_i)\rvert}{\lvert r_o - r_i\rvert} dS_i\right)$	The acceleration $X_n(r_i)$ of each surface element dS_i is weighted and summarized to a acceleration level L_a by neglecting the phase information. Thus the acceleration level L_a is identical with the sound pressure level SPL as long as all elements move in-phase (e.g. piston mode).
Decomposition in radial and circular modes	$x_n(r,\varphi) = x_{cir}(r,\varphi) + \overline{x_{rad}}(r)$	If the loudspeaker cone has a round shape and the excursion $x_n(r,\varphi)$ is measured in polar coordinates r, φ the total excursion can be split into a radial component $\overline{x_{rad}}(r,\varphi)$ and a circular component $x_{cir}(r,\varphi)$
Radial Component	$\overline{x_{rad}}(r) = \frac{1}{2\pi}\sum_{\varphi=0}^{2\pi} x_n(r,\varphi)$	The radial component can be calculated by averaging versus the angle φ. The radial component is useful for comparing the results of axial-symmetrical FEA with real measurements.
Circular Component	$x_{cir}(r,\varphi) = x(r,\varphi) - \overline{x_{rad}}(r)$	The circular component is the difference between total vibration and the radial component. The circular component reveals rocking modes and other circumferential modes.
Sound Pressure related Decomposition	$x_n(r,\varphi) = x_{in}(r,\varphi) + x_{anti}(r,\varphi) + x_{quad}(r,\varphi)$	The total vibration can be split in three components with different contribution to the sound pressure output (constructive, destructive, without effect).
In-Phase Component	$x_{in}(r,\varphi) = \mathrm{Re}_+\{x_n(r,\varphi)\exp(j\arg(p(\omega)) + jk(r_o - r_i)\}$	The in-phase component contributes actively to the sound pressure output
Anti-Phase Component	$x_{anti}(r,\varphi) = \mathrm{Re}_-\{x_n(r,\varphi)\exp(j\arg(p(\omega)) + jk(r_o - r_i)\}$	The anti-phase component reduces the sound pressure output

Quadrature Component	$x_{quad}(r,\varphi) = \operatorname{Im}\{x_n(r,\varphi)\exp(j\arg(p(\omega)) + jk(r_o - r_i))\}$	The quadrature component does not contribute to the sound pressure at point r_o. The total volume velocity of this component is zero.
Loss factor	$\eta = \frac{f_2 - f_1}{f_0}$	The loss factor is defined by the 3dB decay of the acceleration level $L_a(f_1)$= $L_a(f_o)$ - 3dB below resonance (f_1<f_0) and $L_a(f_2)$= $L_a(f_o)$ - 3dB above resonance (f_2>f_0) at the natural frequency f_0.

Requirements

Start Up

To perform Cone diagnostics the following equipment is required:

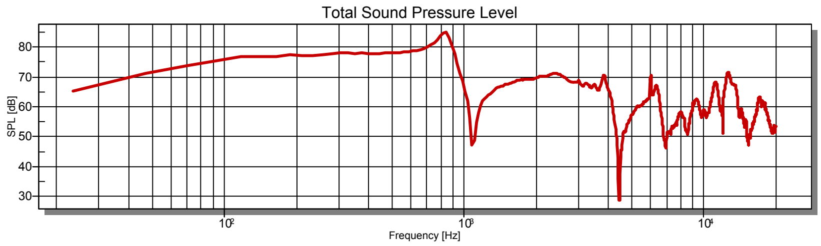
- Install the SCN Analysis Software on your computer
- Click on Scanning data in a file *.ksp to start the analysis

Sound Pressure Output

SPL response in axis

Motivation: We start with the on-axis response which is the most relevant characteristic of the driver and simple to measure and to predict.

How to do it: Select the result page *Radiation Analysis* and set the **Modeling Mode** on *SPL* and select the *Total Vibration. The Model point should be at 1m distance and set all angles (Phi and Theta) to zero.*

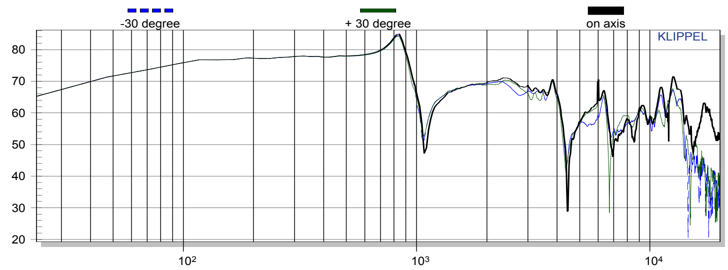


Result: The woofer under test has a flat response above the fundamental resonance (about 80 Hz) up to the 700 Hz. The significant peak at 800 Hz and the dip at 1100 Hz are not acceptable for the particular application.

SPL 30 degree out of axis

Motivation: Considering the size of the normal listening area it is very useful to see the variation of the SPL response for some angles out of axis.

How to do it: Press the button *Export Curves* to store the predicted on axis curve in the database (do not open the database yet).
Set the angle Theta = 30 degree of the Model Point. Store again the result of the current simulation in the same database.
Set the angle Theta= -30 degree and store the third simulation in the database.
Now open the database with dB-Lab.
You find three operation CAL Scanner Results 1, 2 and 3. The window Input Variables shows the details of each simulation. The Total SPL curves can be copied and pasted into a common window. The window below shows the overlay of the three curves:

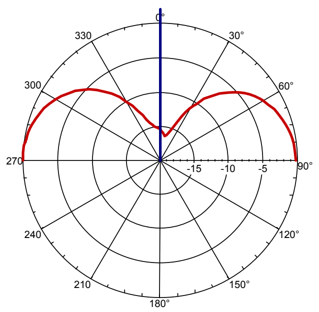


Results: The critical peak and dips appear also out of axis. Significant differences occur at higher frequencies.

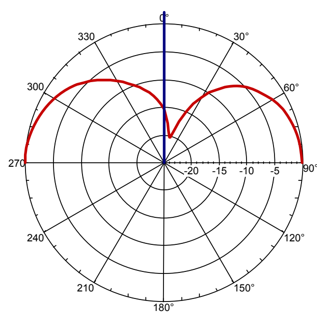
Directivity plot

Motivation: For critical frequencies (where the peaks and dips occur) it is useful to investigate the variation of the SPL response over a larger variation of the angle. This is important for the radiated sound power which determines the diffuse sound in enclosed spaces (rooms).

How to do it: Select the result page **Radiation Analysis** to view the directivity plot. Select a frequency of interest (here at 1 kHz where the dip occurs) by entering the number or by setting the cursor in the SPL plot directly into the dip. Keep the distance r= 1m but set angle Phi to 0° to view the directivity in the horizontal plan. You may export the directivity plot by moving the cursor on the plot, click the right mouse button and use the popup menu entry *Export Dialog*. Change angle Phi to 90° to see the directivity in the vertical plan.



Directivity at the first dip frequency in the horizontal plan



Directivity at the first dip frequency in the vertical plan

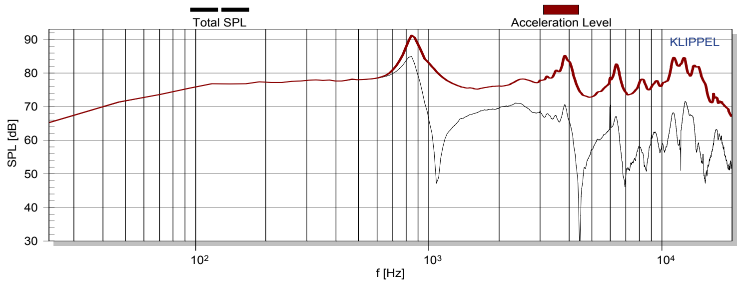
Results: The critical dip at 1 kHz becomes less dominant for a larger angle outside the axis. This indicates that the dip is an acoustical cancellation effect. The total sound power is much less affected by the cancellation than the on-axis SPL response.

Vibration Analysis

Sufficient Vibration?

Motivation: Without cone vibration there is no radiated sound! We recommend to start the vibration analysis by calculating the total acceleration level which summarizes the mechanical vibration and shows the maximal possible SPL if no acoustical cancellation would occur.

How to do it: Select the checkbox *Acceleration* under **Modeling Mode** and the acceleration level will be displayed. We recommend to export all curves to dB-Lab by pressing the button *Export Curves* and to compare the Acceleration level with the total on axis SPL level. After selecting the two curves you will see window like this:

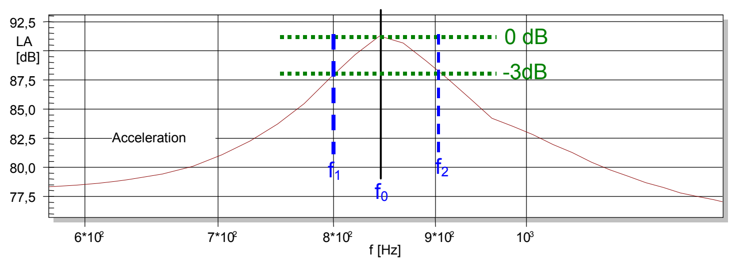


Results: The acceleration level is identical with the on-axis SPL response at lower frequencies where the cone vibrates as a rigid body. At higher frequencies we see the peaks in the acceleration level which occur at the natural frequencies of the mechanical modes.
The woofer in the current example produces a significant peak in the acceleration level at 850 Hz which causes the first peak in the SPL response. The other peaks at 4 kHz and above generate no excessive peaks in the SPL. It is interesting to see that there are no sharp dips in the acceleration level. Above 15 kHz the acceleration level decreases because the mass of the moving voice coil becomes dominant and is the final limit of the working range.

Sufficient Damping?

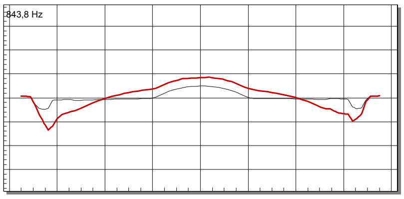
Motivation: The height and sharpness of the peaks in the acceleration level show the loss factor η in the material. We recommend to read this number to compare different materials and treatments.

How to do it: Select the checkbox *Acceleration* under **Modeling Mode** zoom into the first peak of interest. Use the cursor to read dB value $L_a(f_o)$ and natural frequency f_0 of the resonance peak and search for the 3dB decay point $L_a(f_1)= L_a(f_o)$ - 3dB below resonance ($f_1<f_0$) and the other 3dB point above resonance $L_a(f_2)= L_a(f_o)$ - 3dB above resonance ($f_2>f_0$) and calculate the modal loss factor η using the definition presented above.

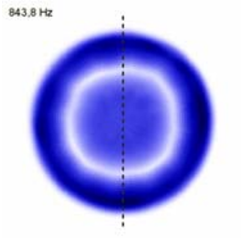


Results: The loss factor η is about 0.1 for the first natural mode occurring 850 Hz. To suppress the peak in the SPL response the loss factor has to be increased by factor 2 or more.

How to increase the loss factor?	**Motivation:** More information is required to find the critical part (cone, surround, glue) where a replacement of the material or a treatment may be useful. This information lies in the shape of the vibration mode at the natural frequency f_0. The vibration mode should be overlaid with the actual geometry to simplify the localization of the problem. **How to do it:** Set the cursor to the natural frequency f_0 where the high peak occurs in the *Acceleration* level. Select the result page *Cross-section View* and set the **Amplitude Enhancement** to zero or to a value which is appropriate for visualization. It is also recommended to view the amplitude plot on result page **Radiation Analysis**.



Cross section view of geometry (black) and displaced geometry (red)



Amplitude plotted as color intensity

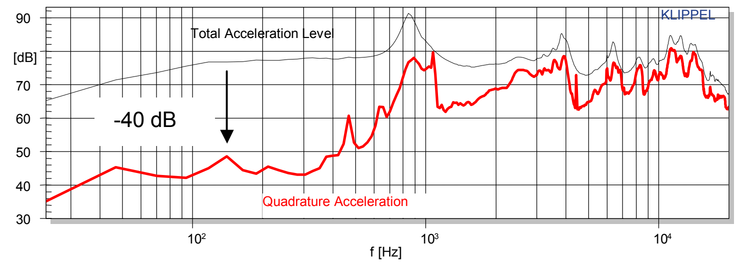
Results: The cross sectional view (left) reveals a first bending mode. We have positive and negative excursion at the same time. The intensity plot (right) shows the largest amplitude at the surround. There is a single node at r=40 mm where is no displacement.

There are three alternatives to increase the damping: It is possible to increase the damping of the cone material (polypropylene). Coating the cone on the outer rim with a viscous material is also possible. Coating at the node has not much effect on the total damping and also applying the coating only at the centre r < 40 mm is also less efficient than at the rim because the area is much smaller. The most effective solution is to use a surround material with a higher loss factor derived from the acceleration curve (see above).

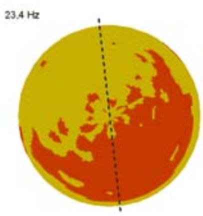
Rocking Modes?

Motivation: The first circumferential mode may be interpreted as a rocking movement of the cone. This may cause a rubbing of the voice coil in the gap and produce audible distortion and a permanent damage of the speaker. Any variation of the cone and surround geometry versus the angle (e.g. varying thickness) may cause an asymmetry in the mass distribution which initializes and supports circumferential modes. The weight and flexibility of the wires and the position of the connection point on the cone are also critical. Note the rocking modes may have significant amplitude in the acceleration level but can not be detected in the radiated sound pressure output. The best indicator for circumferential modes is the quadrature component of the acceleration level.

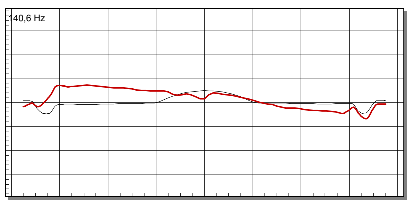
How to do it: Select the checkbox *Acceleration* under **Modeling Mode,** activate the check box *SPL related* under **Decomposition** and select the *Quadrature Component* in the checkbox below. Open the result page *Radiation Analysis* and look for the Quadrature component in the acceleration level which appears as a red thick curve in the window below. Search for peaks in the Quadrature component occurring at lower frequencies. In the current example woofer there is only a minor peak at 150 Hz.



To view the rocking mode activate *Phase* under Color Mode and set the cutting line for the cross sectional view rectangular to the border of positive and negative phase (red and yellow areas) as shown below. Select the result page *cross sectional view.*



Phase plot of the rocking mode at 150 Hz and cutting line (dashed line) for the sectional view



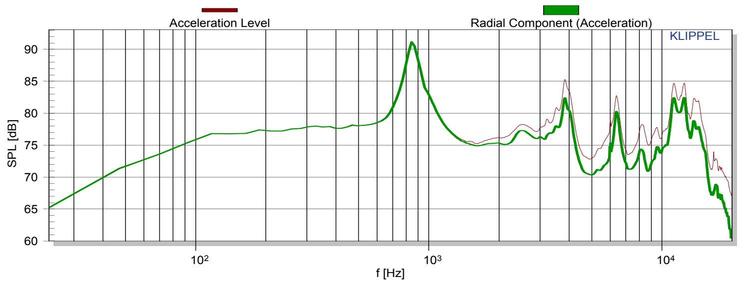
Cross-sectional view showing the excursion of the rocking mode (red curve) compared with the geometry of the cone (black curve).

Result: The rocking mode at 150 Hz is 40 dB below the total vibration which shows that this particular woofer is not very sensitive for voice coil rubbing.

Comparison with FEA

Motivation: At a certain point it is required to perform a finite element analysis of the cone vibration. The cone geometry measured by the Scanner at high precision may be used as an input as well as the loss factor $\eta(f_i)$ determined at the natural frequencies f_i from the acceleration response (see above). The thickness of the cone has to be measured separately and has a high impact on the natural frequencies of the bending modes. The Young's E modulus highly depends on frequency and temperature and precise data is usually not available.
It is a common practice to find good input parameters by fitting the predicted curve to the measured curve. Since most of the FEA tools are based on an axial-symmetrical model the circular modes in the measured vibration have to be suppressed. For cones with a round shape the radial vibration component is the best response for comparing predicted and measured vibration.

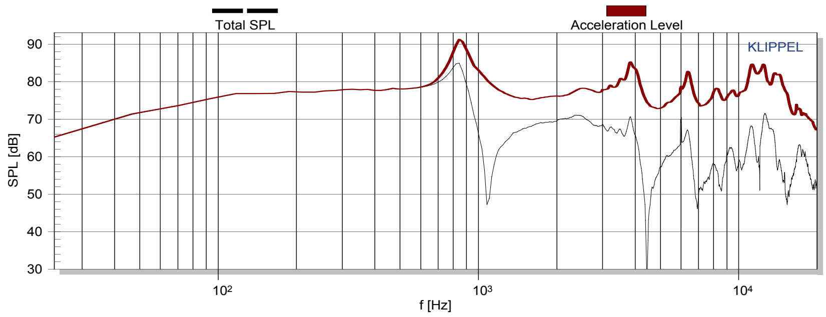
How to do it: Activate the checkbox Acceleration under Modeling Mode and select the checkbox *Radial* under **Decomposition** method and in the combo box *Radial component*.



Radiation Analysis

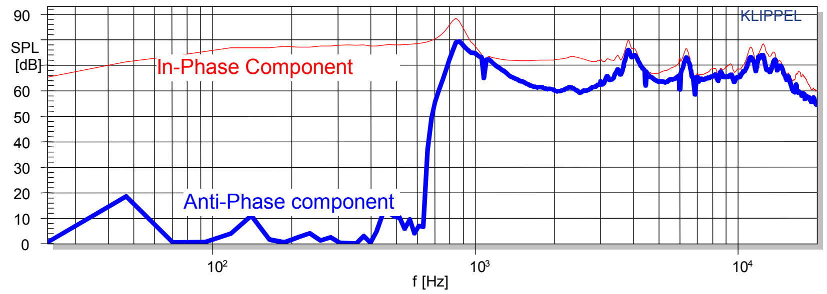
Acoustical Cancellation?

Motivation: Above the cone break-up frequency different cone segments move with a phase difference larger +- 90 degree. Thus some cone segments produce a volume velocity with different sign which reduces the total acoustical output. Significant differences between the acceleration and SPL response give already some clues for a radiation problem. The sharp dips in the SPL response as shown at 1.1 kHz, 4.4 kHz and 7 kHz are also indicators for acoustical cancellation.



A better criterion is the comparison of the in-phase and anti-phase component which gives also some suggestion for constructional improvements.

How to do it: Press the button *Export Curves* at the lower right corner of the SCN Scanning software and open dB-Lab to compare the in-Phase and Anti-Phase component in the SCN Result Curves - SPL Decomposition.



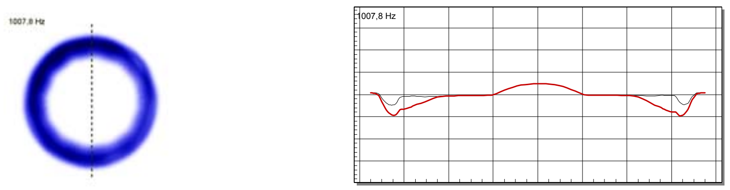
Results: The response of the In-Phase component (thin red curve) is very similar to the response of the acceleration level. Below break-up the In-phase component is actually identical but above cone break-up this curve is only a few dB lower. The reason is that the Anti-phase component (thick blue curve) is almost zero when the cone moves as a rigid body and increases rapidly at the cone break up (about 700 Hz). While the In-phase component actively contributes to the radiated sound the anti-component reduces the output. Acoustical cancellation occurs when the in-phase and anti-phase components become equal in level. This occurs at the same frequencies at 1.1 kHz, 4.4 kHz and 7 kHz where the SPL response shows the dips.

Conclusion: Loudspeaker which have a dominant in-phase component which is at least 6 dB higher than the anti-phase component will not suffer from acoustical cancellation.

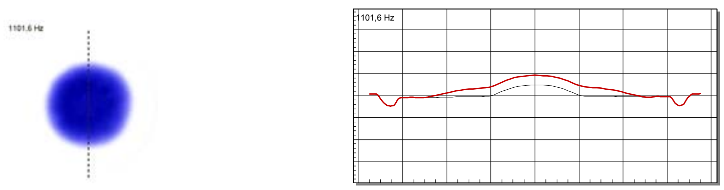
Where is the sound generated?

Motivation: To avoid or fix acoustical cancellation problems we have to support the vibration mode which is in phase with the radiated output. The first step is to understand where the in-phase component is generated.

How to do it: Activate the checkbox *SPL* under **Modeling Mode** and select the *In-Phase Component* under **Decomposition** *SPL related*. Select a frequency just below the cancellation frequency (here 1000 Hz) and view the intensity plot on the result page Radiation Analysis. Select a second frequency (1100 Hz) which is just above the cancellation frequency and compare the two plots.

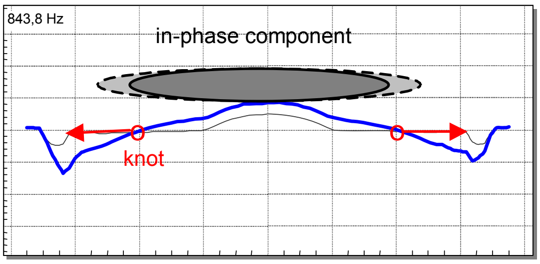


Intensity plot and cross-sectional view of the in-phase component at 1000 Hz



Intensity plot and cross-sectional view of the in-phase component at 1100 Hz

Result: The in-phase component below the critical cancellation frequency is found at the outer part of the cone and above the cancellation frequency it is found in the center of the cone. The in-phase component switches its position also at 4.4 kHz, 7 kHz, 8.5 kHz, 10 kHz and 15 kHz.



A dominant in-phase component avoids acoustical cancellation effects. Keep the area of the in-phase component as large as possible !

Remedy: At low frequencies where the cone moves as a rigid body (piston) the In-phase component also covers the inner part of the cone. Thus we have to keep the In-phase component at higher frequencies in the inner part of the cone. Conventional paper cones with an apex angle with less than 70 degree break up gradually from the outside rim. The first bending node occurs close to the outer rim of the paper cone and the In-phase component always stays in the center of the cone but decreases in size with rising frequency when more and more nodes occur.
Flat cones with a high apex angle (> 70 degree) need some tricks to change the shape of the first natural modes. Using a material with a different Young's E modulus will usually not solve this problem because the cancellation point will only be shifted in frequency. Increasing the damping of the cone is also not effective. We recommend to vary the thickness of the cone material to generate more bending stiffness in the center. This can also be obtained by using additional rips below a flat cone. Increasing the mass of the surround or varying the mass distribution on the cone is also an effective way to get the first nodes close to the outer rim of the cone.

More Information

Papers

W. Klippel, J. Schlechter, "Measurement and Visualization of Loudspeaker Cone Vibration," presented at the 121st Convention of the Audio Eng. Society, 2006, October 5-8

F.J.M. Frankort, "Vibration Patterns and Radiation Behavior of Loudspeaker Cones," J. of Audio Eng. Soc., Sept. 1978, Vol. 26, pp. 609- 622.

C. Struck, "Analysis of the Nonrigid Behavior of a Loudspeaker Diaphragm using Modal Analysis," presented at 86th convention of Audio Eng. Soc., Hamburg, 1989, preprint 2779.

D. A. Barlow, et. al., "The Resonances of Loudspeaker Diaphragms," presented at the 65th Convention of the Audio Eng. Soc., February 1980, preprint 1590.

updated April 4, 2012

KLIPPEL

Klippel GmbH
Mendelssohnallee 30
01309 Dresden, Germany

www.klippel.de
info@klippel.de

TEL: +49-351-251 35 35
FAX: +49-351-251 34 31