Hands-On Training 2

Vibration and Radiation Behavior of Loudspeaker's Membrane

1 Objective of the Hands-on Training

- Understanding the need for distributed parameters to model loudspeakers at higher frequencies
- Applying laser scanning techniques to electro-acoustical transducer
- Interpreting the results of modal analysis
- Refreshing the basic theory of sound radiation and propagation
- Performing sound radiation analysis
- Developing skills in loudspeaker diagnostics to assess quality and choose between design choices

2 Requirements

2.1 Previous Knowledge of the Participants

It is recommended to do the previous *Klippel Training 1 "Linear Lumped Parameter Measurement"* before starting this training.

2.2 Minimum Requirements

The objectives of the hands-on training can be accomplished by using the results of the measurement provided in a Klippel database (.ksp). (A complete setup of the KLIPPEL measurement hardware is not required). The data may be viewed by downloading the *SCN Analysis Software* (version 2.0.11 or later) and the measurement software *dB-Lab* from www.klippel.de/training and installing them on a Windows PC.

2.3 Optional Requirements

If the participants have access to a KLIPPEL R&D Measurement System we recommend to perform some additional measurements on transducers provided by instructor or by the participants. In order to perform these measurements, you will also need the following additional software and hardware components:

- Scanning Control Hardware
- 3D Scanner
- Distortion Analyzer DA2 or Klippel Analyzer 3 KA3
- Laser Sensor + Laser Controller
- Amplifier
- Driver Stand

3 The Training Process

1. Read the theory that follows to refresh your knowledge required for the training.
2. Watch the demo video to learn about the practical aspects of the measurement.
3. Answer the preparatory questions to check your understanding.
4. Follow the instructions to interpret the results in the database and answer the multiple-choice questions off-line.
5. Check your knowledge by submitting your responses to the anonymous evaluation system at www.klippel.de/training.
6. Receive an email containing a **Certificate with high distinction, distinction or credit** (depending on your performance).
7. Perform some optional measurements on transducers if the hardware is available.

4 Introduction

At low frequencies, the motor and mechanical system of a loudspeaker can be modeled by an equivalent circuit using lumped parameters. The electrical signals (voltage u and current i) at the terminals generate the electro-dynamical force F_{coil} driving the moving mass M_{ms}, stiffness of the suspension K_{ms} and mechanical resistance R_{ms} and generating the voice coil velocity v_{coil}. An electrical signal (e.g. voltage u) and a mechanical signal (e.g. velocity v) describe the transfer of the audio signal in a one-dimensional signal path (see Training 1). At higher frequencies, a distributed model comprising a multitude of parameters and state variables is required to describe the vibration of the diaphragm and suspension system. The velocity $v(\boldsymbol{r}_c)$ in the normal direction at any point $\boldsymbol{r}_c$ on the radiating surface generates the sound pressure values $p(\boldsymbol{r}_n)$ and $p(\boldsymbol{r}_a)$ in the near and far field, respectively.

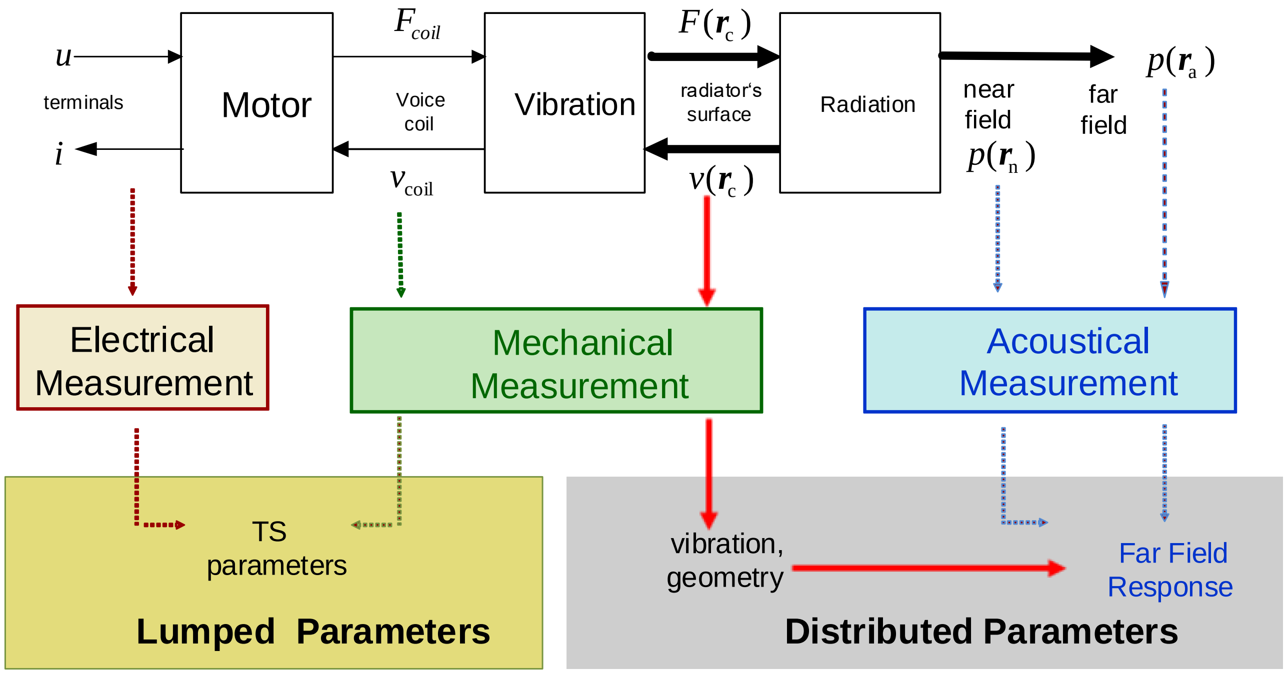


Figure 1: Loudspeaker parameters

Although mechanical vibration plays an important role in the generation of the reproduced sound, its measurement has been much more difficult in the past than the measurement of electrical input signals and acoustical output signals. Modern laser scanning techniques measure the mechanical vibration and the geometry of the cone with high accuracy. The SCN Analysis Software supports the visualization and animation of the measured data and provides new kinds of analyses for cone vibration and prediction of the radiated sound pressure.

4.1 Displacement Transfer Function

The laser scanner provides the complex transfer function

$$\underline{H}_x(j\omega,\boldsymbol{r}_c)=\frac{\underline{X}(j\omega,\boldsymbol{r}_c)}{\underline{U}(j\omega)} \qquad (1)$$

between the voltage signal u at the loudspeakers terminal and the displacement x at an arbitrary point $\mathbf{r}_c$ on the radiating surface.

The exact position of the measuring points is recorded and describes the geometry of the membrane surface. The number of scanning points on the measured grid varies between 50 to 3200, depending on the application (see demo video).

Figure 2 shows an example of transfer function response of a loudspeaker. The red arrow indicates the resonance frequency of the woofer at $f_s \approx 50$ Hz. Below the resonance, the transducer generates constant voice coil displacement because the entire excitation force drives into the mechanical suspension (assuming constant stiffness). Above resonance, the response falls by 12 dB/octave approximately. Above 1 kHz there are significant deviations from this behavior due to vibration modes breaking up on the cone. This will be discussed in the following sections.

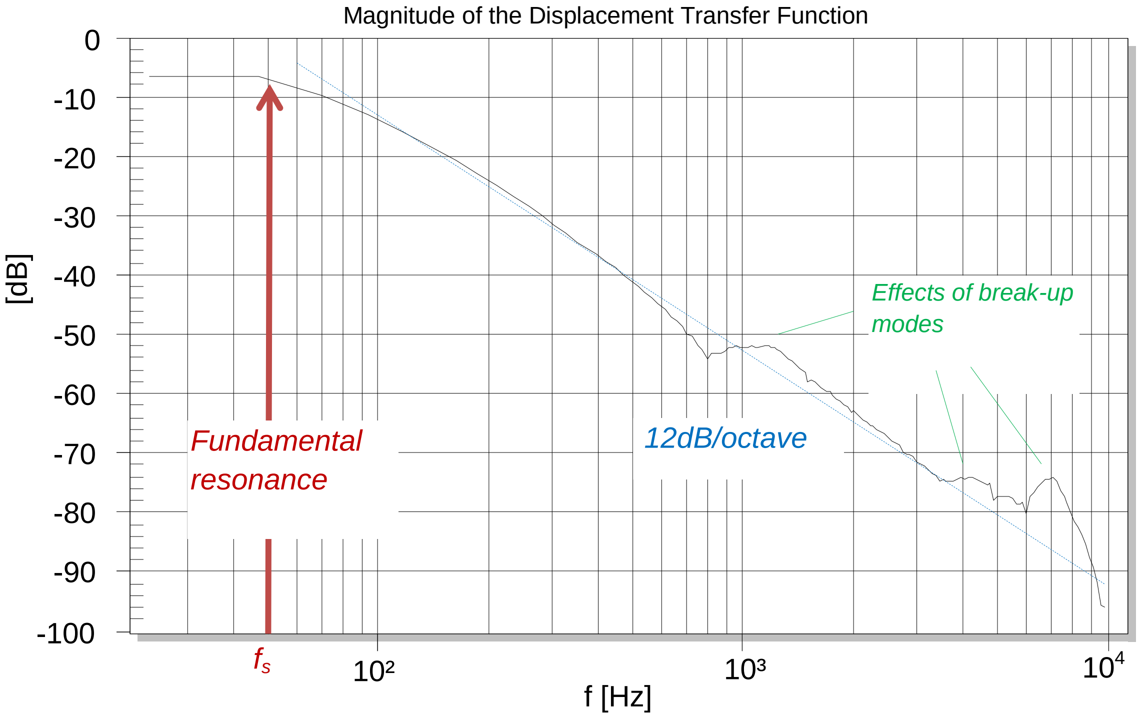


Figure 2: Magnitude of Transfer Function $\underline{H}_x(j\omega, r_c)$ between input voltage and displacement at point r_c

4.2 Accumulated Acceleration Level

The amplitude of the vibration of the radiator may be summarized in an **A**ccumulated **A**cceleration **L**evel (AAL) defined by

$$AAL(\boldsymbol{r}_a) = 20\log\left(\frac{p_{aa}(\boldsymbol{r}_a)}{\sqrt{2}p_o}\right)\text{dB} \qquad (2)$$

using the sound pressure potential

$$p_{aa}(\boldsymbol{r}_a) = \frac{\rho_0\omega}{2\pi}\int_{S_c}\frac{|\underline{v}(\boldsymbol{r}_c)|}{|\boldsymbol{r}_a - \boldsymbol{r}_c|}dS_c \qquad (3)$$

with

ρ_0	density of air
S_C	surface of the membrane
r_c	point in the surface element dS_c
r_a	observation point in the far field
p_0	reference sound pressure

and the velocity

$$\underline{v}(j\omega, \boldsymbol{r}_c) = j\omega\underline{H}_x(j\omega, \boldsymbol{r}_c)\underline{u}(j\omega) \qquad (4)$$

expressed by using the terminal voltage u and the transfer function $H_x(j\omega,\mathbf{r}_c)$ measured by laser scanning.

The sound pressure potential p_{aa} describes the maximal sound pressure at point $\boldsymbol{r}_a$ in the far field while neglecting phase information due to the distance $|\boldsymbol{r}_a - \boldsymbol{r}_c|$ and considering the magnitude of velocity v only. Therefore the AAL is always larger or equal than the **S**ound **P**ressure **L**evel (SPL) as shown in Figure 3.

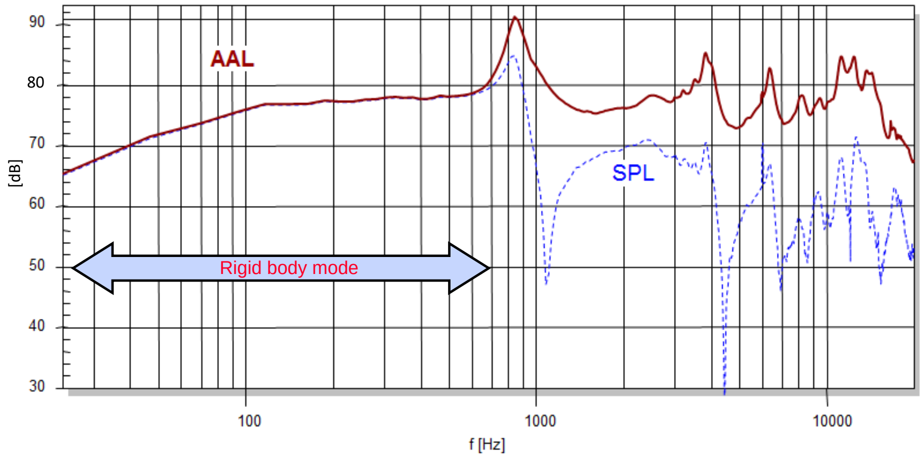


Figure 3: Comparison AAL and SPL curves at the same observation point $\boldsymbol{r}_a$

At low frequencies, below cone break up (at 800 Hz, in Figure 3), the SPL is identical with the AAL. At higher frequencies the AAL reveals distinct peaks which correspond to modal resonances on the cone. In contrast, the SPL response shows significant dips at higher frequencies, which correspond to destructive interferences in the acoustical radiation.

4.2.1 Modal Analysis

The peaks in the AAL response correspond to resonances of distributed vibration-modes which are similar to the fundamental resonance f_s where the loudspeaker can be modeled by lumped parameters. The mode-shapes are mutually orthogonal and can be used as structural functions in a series expansion

$$\underline{a}(\boldsymbol{r}_c) = \sum_{i=0}^{\infty} \underline{H}_i(j\omega)\psi_i(\boldsymbol{r}_c) \qquad (5)$$

where $\psi_i(\boldsymbol{r}_c)$ describes the local distribution of the vibration along the mode-shape and $\underline{H}_i(j\omega)$ the frequency response for each vibration mode:

$$\underline{H}_i(j\omega) = \frac{\omega^2}{1 + \eta_i j\omega/\omega_i - (\omega/\omega_i)^2} \qquad (6)$$

The modal loss factor

$$\eta_i = \frac{\omega_2 - \omega_1}{\omega_i} = \frac{f_2 - f_1}{f_i} \qquad (7)$$

at the natural frequency ω_i can be determined after reading the 3 dB bandwidth f_2 - f_1 as illustrated in Figure 4.

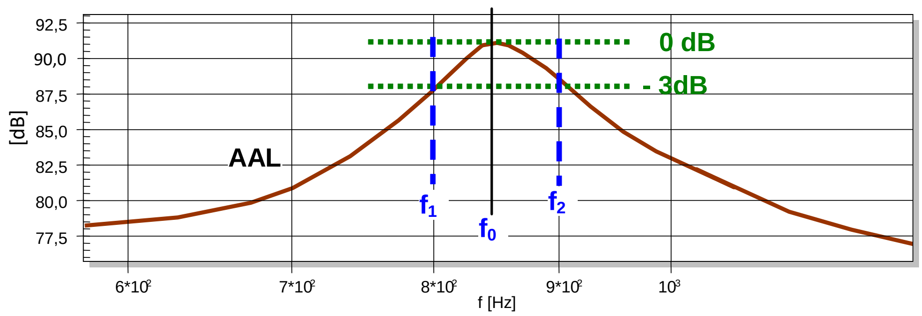
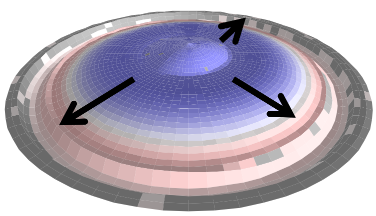


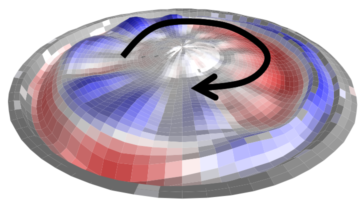
Figure 4: Reading the relative 3 dB bandwidth in the AAL curve

4.2.2 Axial Symmetrical Decomposition

If the loudspeaker cone has a round shape the total vibration can be split in radial and circumferential (circular) components. The modes propagating in radial direction can be calculated by averaging the vibration *v* versus the circumferential angle φ giving the radial velocity as illustrated in Figure 5. The circumferential modes are the difference between total vibration and the radial component:



$$\underline{v}_{\text{rad}} = \frac{1}{2\pi}\int_0^{2\pi} \underline{v}_{\text{total}}(\varphi)\,\mathrm{d}\varphi \qquad (8)$$



$$\underline{v}_{\text{circ}} = \underline{v}_{\text{total}} - \underline{v}_{\text{rad}} \qquad (9)$$

Figure 5: Separation of radial and circumferential mode in transducers with round geometries

Figure 6 shows that the **A**ccumulated **A**cceleration **L**evel (AAL) of the circumferential modes rises with the frequency. Circumferential modes with high amplitude may produce significant nonlinear distortion but produce low **S**ound **P**ressure **L**evel (SPL) on-axis. However, circumferential modes generate significant side lobes resulting in a low **D**irectivity **I**ndex (DI) (equation 17). The lowest circumferential component is a rocking mode which may cause voice coil rubbing in the gap.

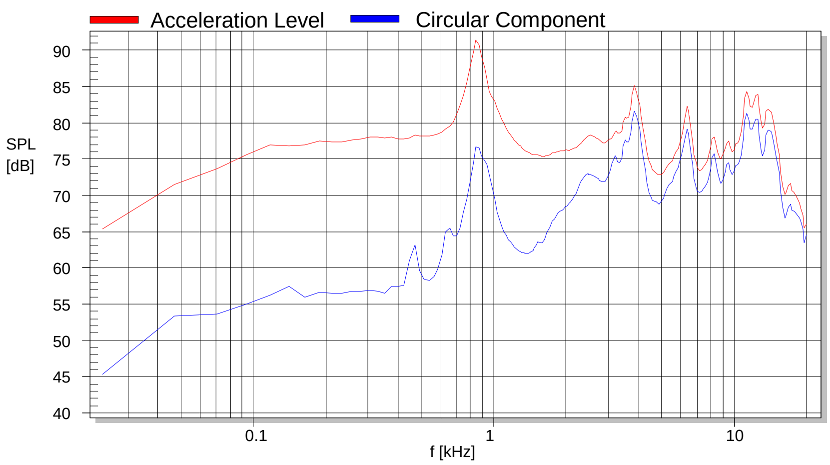


Figure 6: AAL of the total vibration (red) and AAL of the circumferential component (blue) versus frequency

4.3 Sound Radiation

The sound pressure $p(\boldsymbol{r}_a)$ at an observation point $\boldsymbol{r}_a$ in the far-field generated by a vibrating surface S_c can be approximately calculated by describing the sound radiation at each point $\boldsymbol{r}_c$ on the surface by a monopole generating a volume flow $dQ = v(\boldsymbol{r}_c)dS_c$ according to the velocity v and the corresponding area dS_c.

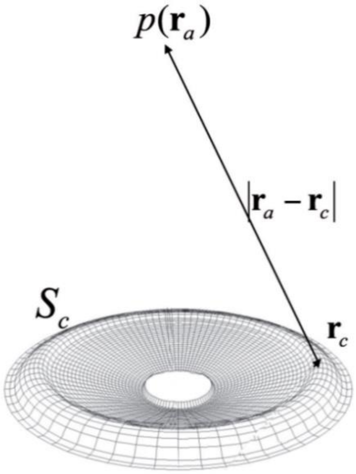


Figure 7: Sound Radiation modeled by equivalent monopoles on the cone's surface

If the radiator's surface is mounted in a baffle, the total sound pressure at a point $\boldsymbol{r}_a$ in the far field can be calculated by integrating the contribution of all monopoles using the first *Rayleigh* integral (10) [compare also equation (3)]

$$\underline{p}(\boldsymbol{r}_\mathrm{a}) = \frac{j\omega\rho_0}{2\pi}\int_{S_\mathrm{c}} \frac{\underline{v}(\boldsymbol{r}_\mathrm{c})}{|\boldsymbol{r}_\mathrm{a} - \boldsymbol{r}_\mathrm{c}|} e^{-jk|\boldsymbol{r}_\mathrm{a}-\boldsymbol{r}_\mathrm{c}|} dS_\mathrm{c} \qquad (10)$$

using density of air ρ_0. The exponential $e^{-jk|\vec{r}_a - \vec{r}_c|}$ produces the phase shift, which results from the time required for the sound wave traveling from the source point $\boldsymbol{r}_c$ to the observation point $\boldsymbol{r}_a$. The denominator $|\boldsymbol{r}_a - \boldsymbol{r}_c|$ describes the attenuation of the sound with rising distance between source and observing point. The **S**ound **P**ressure **L**evel (SPL) is defined by

$$SPL(\omega, \boldsymbol{r}_\mathrm{a}) = 20\log\left(\frac{|p(j\omega, \boldsymbol{r}_\mathrm{a})|}{\sqrt{2}p_\mathrm{o}}\right)\mathrm{dB} \qquad (11)$$

using reference sound pressure p_0.

4.3.1 Beam Pattern

Figure 8 shows the beam pattern, which is the variation of the relative sound pressure on a sphere in the far field over an azimuthal angle ϕ and an elevation angle θ .

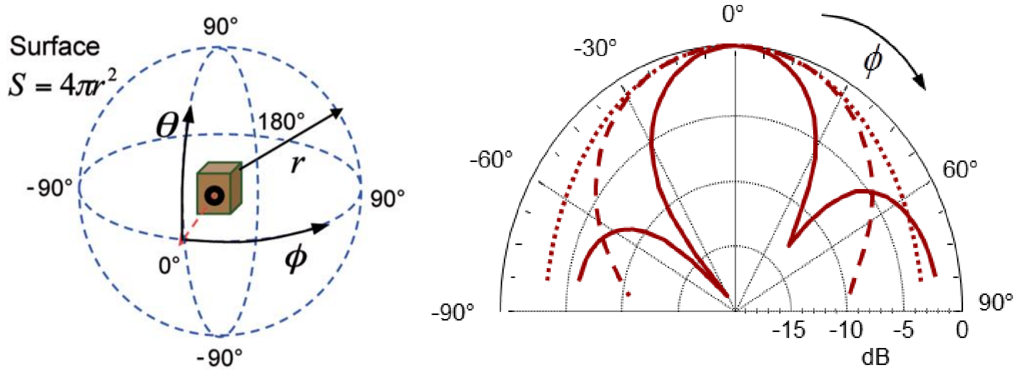


Figure 8: Beam Pattern

The beam pattern is defined by

$$b(\theta,\phi) = 20\log H(\theta,\phi)\mathrm{dB} = 20\log\left(\frac{p(r,\theta,\phi)}{p(r,0,0)}\right)\mathrm{dB} \quad (12)$$

as the level of the directional factor $H(\theta,\phi)$ which is the ratio of the sound pressure $p(r,\theta,\phi)$ at an observing point at angles ϕ ,θ and radius r and the on-axis sound pressure $p(r,0,0)$ at distance r. Thus the sound pressure level on-axis $SPL_{ax}(r)$ can be described as

$$SPL_{ax}(r) = 20\log\left(\frac{p(r,0,0)}{p_o}\right) dB \quad (13)$$

4.3.2 Sound Power

In far field the total acoustic sound power Π radiated by the source can be obtained by integrating the mean square of the sound pressure on the surface S over the angles θ and ϕ by the following equation

$$\Pi = \frac{1}{\rho_0 c}\int_S p(r,\theta,\phi)^2 \mathrm{d}S \quad (14)$$

using the speed of the sound c. The sound power level L_Π (in dB) is defined as

$$L_\Pi = 10\log_{10}\left(\frac{\Pi}{P_0}\right)\mathrm{dB} \quad (15)$$

using the reference power $P_0 = 10^{-12}$ W.

4.3.3 Directivity

The directivity defined by

$$D = \frac{S}{\int H^2(\theta,\phi)\mathrm{d}S} \quad (16)$$

and the derived Directivity Index in dB

$$DI = 10\log_{10}(D)\mathrm{dB} \quad (17)$$

describe the beaming of the source. For a monopole having an omni-directional radiation characteristic, the Directivity Index equals 0 dB.

When operating a radiator (e.g. cone) in an infinite baffle and radiating into half space, it is possible to find a distance $r \approx 0.4$ m between source and observation point where the Directivity Index (DI) is the difference between the sound pressure and sound power level:

$$DI \approx SPL_{ax}\left(r = 0.4\text{m}\right) - L_{\Pi} \qquad (18)$$

Figure 9 shows the most important three responses of a radiator mounted in a baffle. At low frequencies, there is no difference between the three curves because the radiator vibrates as a rigid body and the loudspeaker generates an omni-directional radiation pattern because wave length is much larger than the geometrical dimensions of the radiator. At higher frequencies, where the break-up modes occur, the acoustical cancellation causes a difference between AAL and SPL. The difference between SPL on-axis and Sound Power response at higher frequencies corresponds with the rising Directivity Index and the beaming of the source.

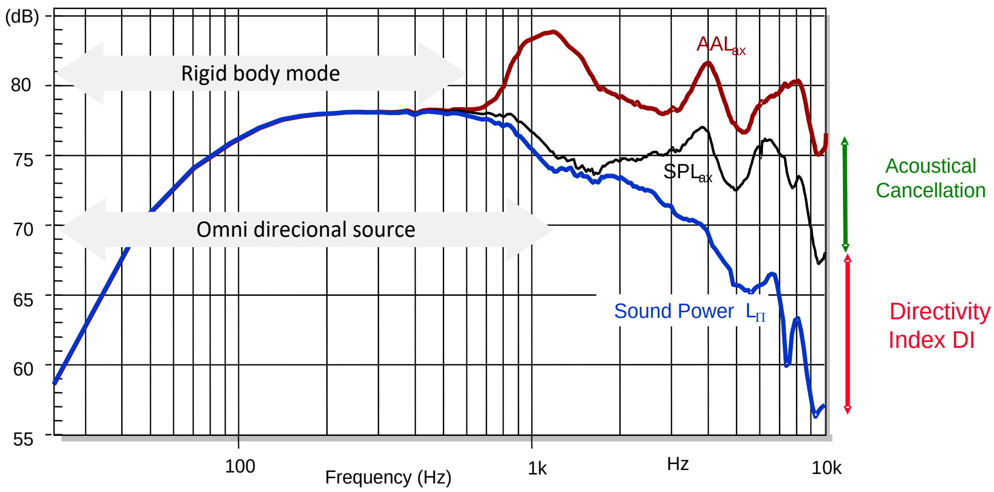


Figure 9: AAL response, sound power response and on-axis SPL responses at a distance r = 0.4 m of a radiator operated in an infinite baffle

4.3.4 Sound-Pressure-Related Decomposition

To explain the acoustical cancellation it is useful to decompose the total vibration into three components:

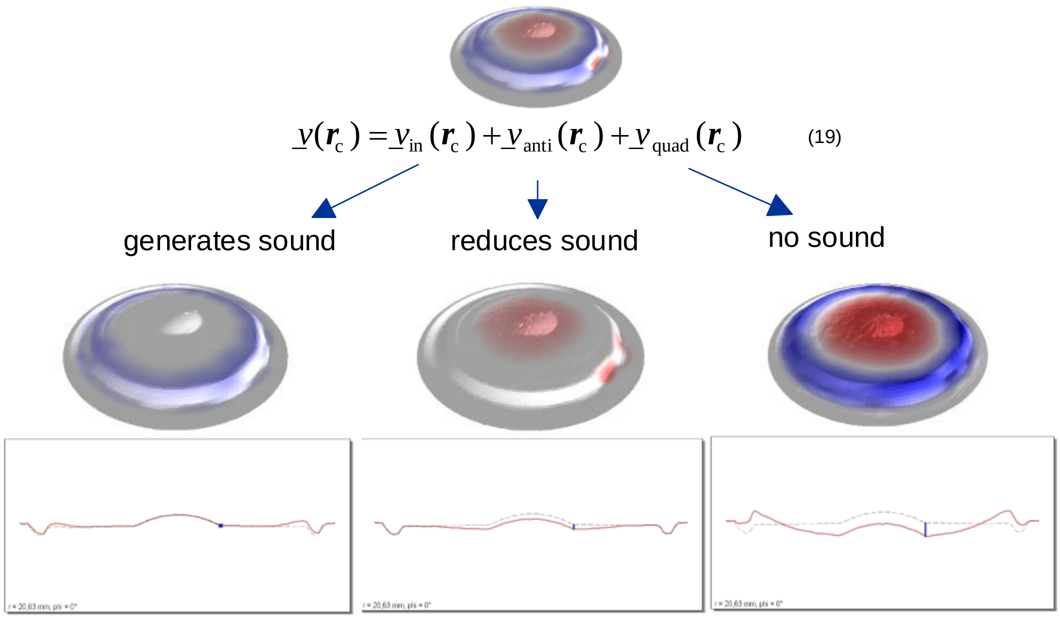


Figure 10: sound-pressure-related decomposition

The in-phase component $\underline{v}_{in}(\boldsymbol{r}_c)$ is a constructive contribution to the sound pressure $\underline{p}(\boldsymbol{r}_a)$ at the observation point $\boldsymbol{r}_a$ in the far-field. The anti-phase component $\underline{v}_{anti}(\boldsymbol{r}_c)$ is a destructive contribution and reduces the sound pressure $\underline{p}(\boldsymbol{r}_a)$. The quadrature component $\underline{v}_{quad}(\boldsymbol{r}_c)$ will be completely compensated by the contributions from other points on the radiator's surface and has no effect on the sound pressure $\underline{p}(\boldsymbol{r}_a)$ at the observation point $\boldsymbol{r}_a$. The KLIPPEL engineering poster "Loudspeaker Sound Radiation" gives a detailed description of the sound pressure decomposition method.

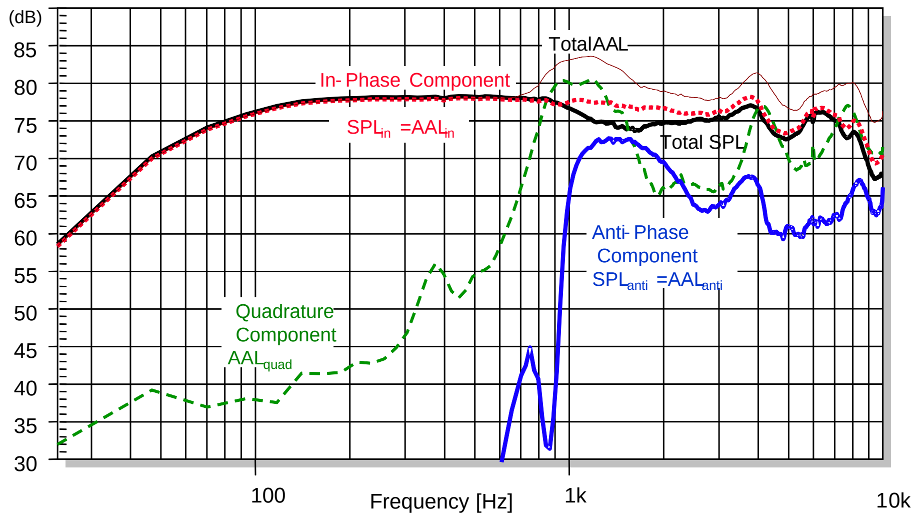


Figure 11: Comparison of sound pressure components with AAL and SPL

The three vibration components can be explained in greater detail in Figure 11, which compares the components with the AAL and SPL responses:

1. The responses $SPL_{in} = AAL_{in}$ of the in-phase component (red, dotted line) may be larger than the total SPL (black, solid line) but never exceeds the total AAL (red, solid line). These curves coincide below cone break-up where the anti-phase and quadrature components are negligible.
2. The responses $SPL_{anti} = AAL_{anti}$ of the anti-phase component (blue, solid line) rise rapidly at the break-up frequency (here about 1 kHz) but never exceed the values of $SPL_{in} = AAL_{in}$ in the in-phase component.
3. The quadrature component produces no sound pressure but the AAL_{quad} may exceed the in-phase component. The peak at 380 Hz indicates a rocking mode.

4.3.5 Acoustical Cancellation

Significant dips in the SPL response are caused by acoustical cancellation which occurs if the anti-phase component is not negligible and the difference between in-phase component SPL_{in} and anti-phase component SPL_{anti} becomes smaller than 10 dB as shown in Figure 12.

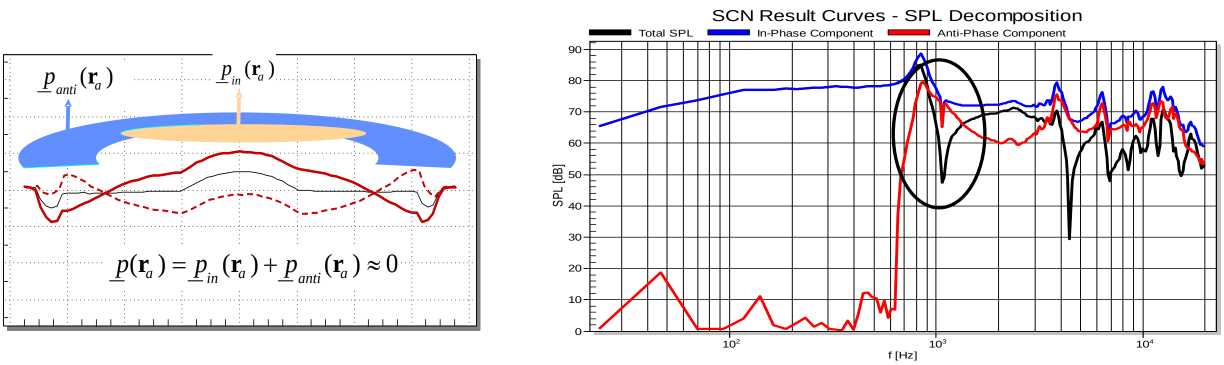


Figure 12: Acoustical cancellation generating dips in the total SPL response

4.4 Rocking Mode

The first circumferential mode on the surround causes a rocking of the cone and a tilting of the voice coil former which usually occurs at frequencies below the pison mode resonance f_s. This may result in voice coil rubbing in the gap producing impulsive distortion.

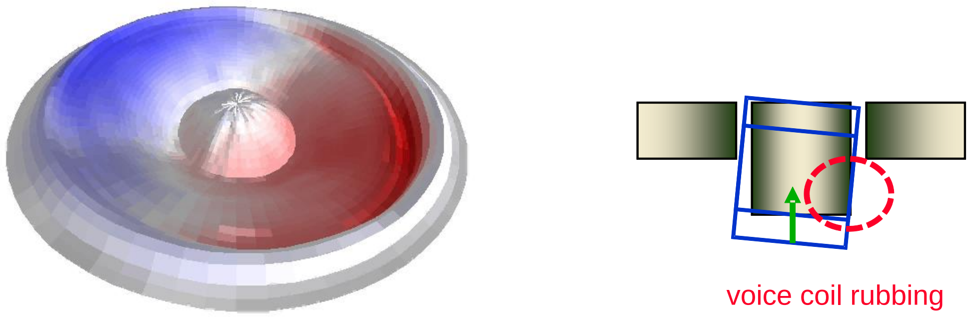
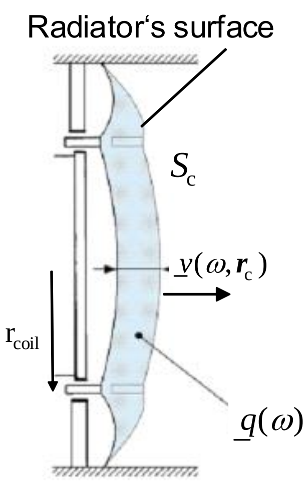


Figure 13: Rocking mode (left) and voice coil rubbing (right)

The rocking mode provides poor radiation conditions, since the radiation surface behaves as two sources (dipole) generating positive and negative volume flow of almost equal source strength generating low sound pressure on-axis. The quadrature component AAL_{quad} is a very good indicator of rocking modes on radiators of arbitrary shape (e.g. rectangular diaphragm).

4.5 Effective Radiation Area

The effective radiation area S_D is an important lumped parameter describing the sound radiation. It is defined as the theoretical surface area S_D of a rigid piston moving with the mean value of the voice coil velocity v_{coil} while generating the same volume velocity $\underline{q}$ as the surface S_c of the loudspeaker. The mean value of the voice coil velocity v_{coil} is calculated by integrating the velocity on a circumference with the voice coil radius r_{coil}. This procedure suppresses rocking and other asymmetrical vibration modes.



replaced by a

$$\underline{S}_D(\omega) = \frac{\int_{S_c} \underline{v}(\omega, \mathbf{r}_c)\, dS_c}{\underline{v}_{coil}(\omega)} \tag{20}$$

using mean voice coil velocity

$$\underline{v}_{coil}(\omega) = \frac{\int_0^{2\pi} \underline{v}(\omega, r_{coil}, \varphi)\, d\varphi}{2\pi} \tag{21}$$

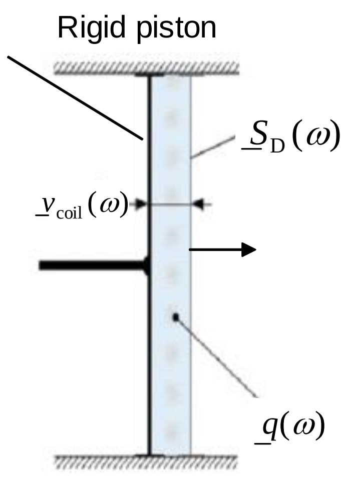


Figure 14: Calculation of the effective radiation area $S_D(\omega)$ versus frequency

Following the definition above, the effective radiation area $S_D(\omega)$ is a function of frequency ω. This function may be used to predict the sound pressure at points with arbitrary distance on the radiation axis. In most cases a single value $S_D = |S_D(\omega_0)|$ is derived from the response by reading the value at the resonance frequency ω_0

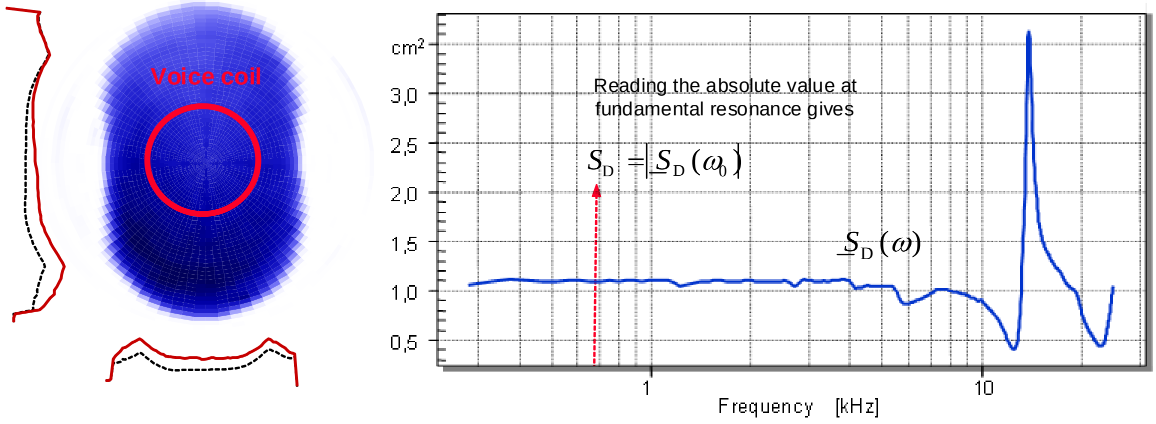


Figure 15: Position of the voice coil (left) and the graphic of the effective radiation area (right)

For woofers, where the width of the surround is small compared to the inner diameter of the cone, the effective radiation area may be approximated by the area using the average of the surround's outer and inner diameter. This approximation fails in micro speakers and transducers for headphones and headsets where the surround area is relatively large and the curved geometry generates a nonlinear decay of the excursion versus the surround.

5 Preparatory Questions

Check your theoretical knowledge before you start the regular training. Answer the questions by selecting all correct responses (sometimes, there will be more than one).

QUESTION 1: How do the cone and the dust cap move at low frequencies?

- □ **MC a:** The cone and the dust cap vibrate as an almost rigid body. All points move with the same amplitude and phase.
- □ **MC b:** The cone and the dust cap vibrate as an elastic body. The points on the surface move with different amplitude and phase.
- □ **MC c:** At particular frequencies the points on the cone and dust cap may vibrate at different amplitude and phase. This is caused by a rocking mode which deforms the surround and spider but tilts the cone and dust cap as a rigid body.

QUESTION 2: What happens to the sound pressure level (SPL) at the receiving point $\boldsymbol{r}_a$ in the far field if the distance between the membrane and the receiving point is doubled? (Use the equation (11) to answer this question.)

- □ **MC a:** The sound pressure increases by 2 dB.
- □ **MC b:** The sound pressure increases by 6 dB.
- □ **MC c:** The sound pressure decreases by 2 dB.
- □ **MC d:** The sound pressure decreases by 6 dB.

QUESTION 3: Compare the equation (11) for the calculation of the sound pressure level (SPL) at the observation point $\boldsymbol{r}_a$ with the equation (2) for the accumulated acceleration level (AAL). Which relationships exist between AAL and SPL?

- □ **MC a:** The AAL and the SPL are almost identical at low frequencies, where the radiator (diaphragm, cone) vibrates as a rigid body and the wave length is much larger than the geometrical dimensions of the radiator.
- □ **MC b:** The SPL is never larger than the AAL at the same observation point $\boldsymbol{r}_a$.
- □ **MC c:** The SPL calculation considers the phase angle of the mechanical vibration and the phase shift caused by the propagation between the source point $\boldsymbol{r}_c$ and the receiving point $\boldsymbol{r}_a$.

- □ **MC d:** The AAL calculation neglects any phase information and corresponds with the maximal sound pressure which would be generated if all points $\boldsymbol{r}_c$ on the membrane would contribute constructively to the total sound pressure SPL at the point $\boldsymbol{r}_a$.

QUESTION 4: Which relationships exist between in-phase, anti-phase and quadrature components?

- □ **MC a:** The AAL_{in} of the in-phase component is never smaller than AAL_{anti} of the anti-phase component.
- □ **MC b:** The AAL_{anti} is always larger than the SPL_{anti} of the anti-phase component.
- □ **MC c:** The SPL_{quad} of the quadrature component is always larger than the SPL_{in} of the in-phase component.
- □ **MC d:** AAL_{quad} is identical with SPL_{quad} of the quadrature component.
- □ **MC e:** AAL_{in} is identical with the SPL_{in} of the in-phase component.

6 Interpretation of Scanning Data (no hardware required)

Step 1: View the demo movie *Vibration and Radiation Behavior of Loudspeaker Membrane* to see how a practical analysis is performed.

Step 2: Download from the website www.klippel.de/training the *Klippel Scanning System SCN* and the *dB-Lab* and install them on your computer. Also download the measurement database.

Advice: It is recommended to do the following exercises offline and to note the answers of the multiple choice questions on a paper!

6.1 Displacement on the Radiator's Surface

Step 3: Click on file **honeycomb.ksp** that is provided in the measurement database to activate the *SCN Analysis Software* to view the results of a laser scan applied to a flat radiator made of honeycomb material.

Step 4: Select the tab ***"Cross Section View".*** Press the button ***"Animation"*** and adjust the ***"Amplitude Enhancement"*** to generate a "natural" vibration of the radiator.

Step 5: Click with the right mouse button on the diagram and activate the ***"Show Current Point"***. Set the cursor to the centre of the radiator to see the magnitude of the transfer *function* $H_x(f)$ between terminal voltage $U(f)$ and displacement $X(f, \boldsymbol{r}_c)$ at this particular point $\boldsymbol{r}_c$.

QUESTION 5: How does the magnitude of the transfer function $\underline{H}_x(f)$ change by doubling the frequency f (70 Hz < f < 5 kHz)?

- □ **MC a:** The magnitude of the transfer function $Hx(f)$ falls with 6 dB per octave approximately.
- □ **MC b:** The magnitude of the transfer function $Hx(f)$ falls with 12 dB per octave approximately.
- □ **MC c:** The magnitude of the transfer function $Hx(f)$ falls with 18 dB per octave approximately.

Step 6: Set the frequency cursor in the lower diagram ***"Displacement Transfer Function"*** to 140 Hz in the file **honeycomb.ksp**. View the magnitude of the transfer function $H_x(f = 140 \text{ Hz}, r)$ as a function of the radius r by setting the blue marker at different locations on the sectional view in the upper diagram.

QUESTION 6: How does the magnitude of the transfer function $H_x(f)$ change versus radius r at low frequencies (f = 140 Hz)?

- □ **MC a:** The magnitude is almost constant over the cone area because this part has a high bending stiffness and moves as a rigid body at low frequencies.
- □ **MC b:** All of the deformation occurs in the surround where the magnitude decreases linearly from the inner edge to the outer edge. Thus the displacement on the middle of the surround is always 6 dB lower than the cone displacement. This is the basis for an accurate calculation

of the equivalent radiation surface S_D by calculating the mean value of inner and outer diameter of the suspension.

- □ **MC c:** The magnitude decreases nonlinearly from the inner edge to the outer edge of the surround. The displacement in the middle of the surround in the particular honeycomb driver is approximately 3 dB lower than the cone displacement. This has some major consequences on the measurement of the equivalent radiation surface S_D (the acoustical measurement gives different results than the geometrical measurement).

6.2 Modal Analysis

Step 7: Select the lower diagram on the tab ***Cross-sectional View*** of the **honeycomb.ksp** and click with the right-mouse button on the animated geometry to deactivate ***"Show current point"***. Select the radio button ***"Acceleration"*** on *Modeling Mode*. Find the natural frequencies by moving the frequency cursor in the lower diagram to the peaks in the acceleration level curve shown in red.

QUESTION 7: Which loudspeaker component(s) is (are) significantly deformed by the modal vibration at the natural frequencies 843 Hz and 6.14 kHz?

- □ **MC a:** 843 Hz: both surround and honeycomb cone; 6.14 kHz; honeycomb cone
- □ **MC b:** 843 Hz: surround; 6.14 kHz: honeycomb cone
- □ **MC c:** 843 Hz: both surround and honeycomb cone; 6.14 kHz: both surround and honeycomb cone;
- □ **MC d:** 843 Hz: surround; 6.14 kHz: surround
- □ **MC e:** 843 Hz: honeycomb cone; 6.14 kHz: honeycomb cone

QUESTION 8: Which natural frequency provides the largest AAL?

- □ **MC a:** The largest mode is at 6.1 kHz.
- □ **MC b:** The largest mode is at 5 kHz.
- □ **MC c:** The largest mode is at 2.5 kHz.

Step 8: Use the cursor to read the 3 dB bandwidth in the AAL response of the **honeycomb.ksp** at the natural frequency 6.14 kHz.

QUESTION 9: Use the equation (7) to determine the modal loss factor at 6.14 kHz.

- □ **MC a:** The modal loss factor η is 0,03 approximately.
- □ **MC b:** The modal loss factor η is 0,3 approximately.
- □ **MC c:** The modal loss factor η is 0,003 approximately.

QUESTION 10: Why is the modal loss factor η at 6.14 kHz much smaller than at 5 kHz?

- □ **MC a:** Because the vibration of the surround is much smaller at 6.14 kHz and the honeycomb material provides less damping than the surround.
- □ **MC b:** Because the vibration of the surround is much smaller at 6.14 kHz and the honeycomb material provides more damping than the surround.

QUESTION 11: How can the modal loss factor η at 6.14 kHz be increased?

- □ **MC a:** Using a different surround material providing more damping.
- □ **MC b:** Using a different spider material providing more damping.
- □ **MC c:** Using a different honeycomb material providing more damping.

QUESTION 12: What are the consequences of a low modal loss factor on the sound pressure output?

- □ **MC a:** Significant peaks in the SPL response which corresponds with long ringing in the cumulative decay spectrum (transient distortion).
- □ **MC b:** High excursion causing nonlinear distortion in the sound pressure output.

- □ **MC c:** Low modal loss factor only affects the mechanical vibration but not the radiation of the sound and has no influence on the sound pressure output.

6.3 Axial Symmetrical Decomposition

Step 9: Open the file **piston driver.ksp**. Select the tab ***Animation***. Switch the *Modelling Mode* to ***"Acceleration"***. Switch the *Decomposition* to ***"Radial"*** and select ***"Total Vibration"***. Press ***"Animation"*** button.

Step 10: Set the frequency cursor in the lower diagram to 140 Hz. Compare the ***"Radial"*** and ***"Circular"*** component with the ***"Total Vibration"*** by selecting the components in *Decomposition*. Adjust the ***"Amplitude Enhancement"*** to view each component.

QUESTION 13: Which modes determine the vibration behavior at 140 Hz?

- □ **MC a:** There is an axial symmetrical mode that dominates the total component.
- □ **MC b:** The circumferential component is almost 20 dB below the AAL of the total vibration and can be neglected.
- □ **MC c:** The circumferential mode affects the spider and the surround causing a small tilting of the piston (rocking mode). Due to the low level this is negligible.
- □ **MC d:** The circumferential and radial components have approximately the same AAL at this frequency.
- □ **MC e:** There is no circumferential mode at this frequency.

Step 11: Set the frequency cursor in the lower diagram to the second peak of the total AAL at 3.9 kHz. Compare the ***"Radial"*** and ***"Circular"*** component with the ***"Total Vibration"*** by selecting the components in *Decomposition*. Adjust the ***"Amplitude Enhancement"*** to view each component properly.

QUESTION 14: Which modes determine the vibration behavior at 3.9 kHz?

- □ **MC a:** There is an axial symmetrical mode which dominates the total vibration (circumferential component is negligible).
- □ **MC b:** There is a dominant circumferential component which dominates the total AAL (radial component is negligible).
- □ **MC c:** The circumferential mode affects the spider and the surround causing a tilting of the piston (rocking mode).
- □ **MC d:** The circumferential and radial components have approximately the same AAL at this frequency.

6.4 Sound Pressure

Step 12: Select in *Modelling Mode* ***"Acceleration"*** and in *Decomposition* ***"SPL related"*** and ***"Total Vibration"***. Set the angles theta $\theta = 0^o$ and phi $\varphi = 0^o$ to see the on-axis response and compare the total AAL with total SPL response.

QUESTION 15: Which relationship exists between the SPL and AAL response?

- □ **MC a:** Below 800 Hz the SPL and AAL response are almost identical because the radiator vibrates as a rigid body.
- □ **MC b:** Sharp peaks in the AAL response correspond to high values in the SPL-response at the same frequency.
- □ **MC c:** Sharp dips in the SPL response correspond to sharp peaks at the same frequency in the AAL response.

6.5 Beam Pattern

Step 13: In the file **piston driver.ksp** view the tab ***Radiation Analysis***. Select the ***"SPL"*** under *Modeling Mode* and ***"Total Vibration"*** under *SPL related Decomposition*. Compare the polar pattern (dependency of SPL on angle θ) shown in the upper left diagram by varying the angles φ (turning the cursor in the upper right diagram).

QUESTION 16: How does the SPL change versus angles φ and θ at 700 Hz, 1.1 kHz and 1.5 kHz?

- □ **MC a:** The SPL variation versus angles θ at both 700 Hz and 1.5 kHz is very small (< 3 dB) producing an almost omni-directional radiation pattern.
- □ **MC b:** The SPL at 1.1 kHz is on-axis ($\theta = 0°$) lower than off-axis (for example, $\theta > 50^{o}$).
- □ **MC c:** The SPL pattern is almost independent of angles φ (turning the cursor in the upper right diagram) for all three frequencies.
- □ **MC d:** There is an omni-directional radiation pattern (constant SPL for any choice of angle φ and θ) at all three frequencies.

QUESTION 17: How does the beam pattern change at the higher natural frequencies 11.2 kHz and 12.5 kHz?

- □ **MC a:** At higher frequencies the loudspeaker produces an omni-directional radiation pattern.
- □ **MC b:** At higher frequencies the loudspeaker produces more SPL on-axis ($\theta = 0°$) than off-axis ($\theta > 50°$).

Step 14: In *Decomposition* mode select the radio button ***"Radial"***and then ***"Circular"*** to see the beam pattern of the circumferential modes on the tab ***Radiation Analysis***. Change the angle φ (turning the cursor in the upper right diagram) and change the frequency cursor in the diagram below.

QUESTION 18: What is the typical radiation characteristic of the circumferential (circular) modes?

- □ **MC a:** The beam pattern has a null on-axis ($\theta = 0°$) for any angle φ and any frequency because circumferential modes generate a regular vibration pattern on the circumference comprising an equal number of positive and negative sound sources having equal source strength approximately and cancelling each other on-axis in the far field.
- □ **MC b:** At low frequencies the SPL raises with rising value of $|\theta|$ because the cancellation effect vanishes off-axis.
- □ **MC c:** Circumferential modes generate an omni-directional radiation pattern.

6.6 Directivity Index

Step 15: In the file **piston driver.ksp** click on ***"Tools"***, select ***"Sound Power"*** and press the button ***"****Start Calculation****"***. Search for frequencies where the directivity index is negative.

QUESTION 19: What does a negative Directivity Index DI = -10 dB mean?

- □ **MC a:** The on-axis SPL is 10 dB smaller than the sound pressure generated by an omni-directional source radiating the same sound power.
- □ **MC b:** The on-axis SPL is 10 dB higher than the sound pressure generated by an omni-directional source radiating the same sound power.
- □ **MC c:** The SPL generated by the radiator in an infinite baffle at a distance 0.4 m on-axis is 10 dB lower than the sound power level.
- □ **MC d:** The SPL generated by the radiator in an infinite baffle at a distance 0.4 m on-axis is 10 dB higher than the sound power level.
- □ **MC e:** The loudspeaker is beaming on-axis.

6.7 Sound Pressure Decomposition

Step 16: In the analysis of the file **piston driver.ksp** select ***"SPL related"*** under *Decomposition*. Set the angle ($\theta = 0°$) to analyze the sound pressure on-axis. Select the ***"In-phase Component"*** and view the vibration pattern at 843 Hz.

QUESTION 20: Where is the sound generated at 843 Hz?

- □ **MC a:** The center of the piston contributes constructively to the sound pressure output on-axis.
- □ **MC b:** The outer area of the piston and the surround contributes constructively to the sound pressure output on-axis.
- □ **MC c:** The complete surround and cone area contributes to the sound pressure on-axis.

Step 17: Compare the vibration patterns of the ***"Quadrature Component"***, ***"Anti-phase Component"*** and the ***"In-phase Component"*** measured at the same frequency 843 Hz. Keep the angle ($\theta = 0°$) to analyse the sound pressure on-axis.

QUESTION 21: To which components can a point r_c on the cone contribute at one particular frequency? (Tip: See Figure 10.)

- □ **MC a:** A point can contribute to the quadrature component and either to the in-phase component or to anti-phase component.
- □ **MC b:** A point can contribute both to the in-phase and to the anti-phase component.
- □ **MC c:** A point can contribute to all three components (quadrature, in-phase and anti-phase).

Step 18: Press the ***"Export Curve"*** button to save the curves in a *.kdbx* file and open this file in dB-Lab. Open the operation ***CAL Scanner Results*** in the object "***Piston Driver"*** and inspect the result window "***Result Curve 1"***. Compare the *In-Phase* and the *Anti-Phase* responses.

QUESTION 22: Are there any frequencies where the *In-Phase* and *Anti-Phase* component have almost similar SPL values?

- □ **MC a:** At the fundamental resonance frequency of the transducer.
- □ **MC b:** At the frequencies where the total sound pressure response shows significant dips (cancellation points).
- □ **MC c:** At the frequencies 1.078 kHz, 4.429 kHz.
- □ **MC d:** At the natural frequencies of the higher order modes where the total AAL response shows local maxima (resonance peaks).
- □ **MC e:** In-phase component is always larger than the anti-phase component.

6.8 Rocking Mode

Step 19: Return to the SCN Analysis Software and select the tab ***Animation***. Select the ***"Quadrature Component"*** under *Decomposition* and keep the angle ($\theta = 0°$) to analyse the AAL on-axis. Switch the *Modeling mode* to ***"Acceleration"***. View the radiation pattern at local peaks of the AAL response. Adjust the ***"Amplitude Enhancement"*** to make the vibration visible.

QUESTION 23: At which frequency occurs the rocking mode?

- □ **MC a:** The rocking mode occurs at 140 Hz and is approximately 28 dB below the AAL of the total component. Thus the rocking mode is not critical.
- □ **MC b:** The rocking mode occurs at 468 Hz and is approximately 17 dB below the AAL of the total component. Thus the rocking mode is not critical.
- □ **MC c:** The rocking mode occurs at 890 Hz and is approximately 12 dB below the AAL of the total component. Thus the rocking mode is not critical.

- □ **MC d:** The rocking mode occurs at 2.5 kHz and is approximately 4 dB below the AAL of the total component. Thus the rocking may be considered as critical because the difference is smaller than 10 dB.

Step 20: Open the file **headphone.ksp** and follow the Step 19:.

QUESTION 24: At which frequency occurs the rocking mode of the headphone transducer?

- □ **MC a:** The rocking mode occurs at 1.8 kHz and is approximately 3 dB below the AAL of the total component and almost identical with the in-phase component. Thus the rocking mode dominates the total vibration and is critical.
- □ **MC b:** The rocking mode occurs at 398 Hz and is approximately 2 dB below the AAL of the total component and 3 dB above the in-phase component. The rocking mode dominates the total vibration and is critical.
- □ **MC c:** The rocking mode occurs at 4.5 kHz and is approximately 13 dB below the AAL of the total component. Thus the rocking mode is not critical.
- □ **MC d:** The rocking mode occurs at 8.3 kHz and is approximately 6 dB below the AAL of the total component. Thus the rocking may be considered as critical because the difference is smaller than 10 dB.

6.9 Effective Radiation Area

Step 21: In the file **headphone.ksp** click on ***"Tools"*** and then *"SD Calculation"* on the menu bar. Set the blue cursor in the upper left diagram to r_{coil} = 7.5 mm where the voice coil is located. View the effective radiation area $S_D(f)$ as a function of frequency.

QUESTION 25: Why does the radiation area $S_D(f)$ rise at higher frequencies (>10 kHz)?

- □ **MC a:** Because there is more movement of the voice coil but less vibration at other areas of the cone at higher frequencies.
- □ **MC b:** Because there is less movement of the voice coil at higher frequencies while other parts of the diaphragm (in the center of the diaphragm) generate sufficient volume velocity.
- □ **MC c:** The quadrature component is rising at higher frequencies decreasing the acoustical output at higher frequencies.

Step 22: Set the blue cursor in the upper left diagram to middle area of the surround (r = 12 mm) and in the centre of the diaphragm (r = 3 mm) and investigate the influence of the radius on the effective radiation area S_D.

QUESTION 26: How does the specified radius r affect the S_D value?

- □ **MC a:** If the specified radius r is larger than the coil radius r_{coil}, the mean velocity v_{coil} of the voice coil is calculated in the surround area where the velocity decreases with radius r. Thus, v_{coil} is smaller than the true value and the effective radiation area S_D is larger than the true value.
- □ **MC b:** If the specified radius r is smaller than the coil radius r_{coil}, the mean velocity v_{coil} of the voice coil is calculated in the center of the cone where the velocity is almost constant. Thus, v_{coil} is correctly measured and the error in the calculation of the effective radiation area S_D is negligible.
- □ **MC c:** The radius r has only a minor influence on the S_D calculation.

7 Performing a Vibration Scan (Hardware required)

If the scanning hardware is available it is recommended to perform a scan on a transducer provided by the instructor or the participants. The target of the optional experiment is to determine the influence scanning grid and the number of points determining the scanning time.

7.1 Information to the Scanner Hardware

The demo movie *Vibration and Radiation Behavior of Loudspeakers Membrane* gives you some practical tips how to use the scanner hardware and software. A detailed description of the hardware setup is provided in the manual.

7.2 Performing a Short Profile Scan

Step 23: Start the software Klippel *Scanning System SCN*.

Step 24: In the *File* menu select ***Perform New Scan***. The shortest scan is the profile scan which uses an asymmetrical grid on one angle only.

Step 25: After the initialization steps a new scanning project can be started. Create a *Project File* and give it the name **“profile scan.ksp”**.

Step 26: Leave the *Scan Setup* with the default setup and proceed to the ***Measurement Grid Setup***.

Step 27: In *Grid* choose ***Profile Grid*** in *Preset* to measure a single cross-line and enter the ***Outer Radius*** of your driver. Click on ***“Save and Start”***.

Step 28: Follow the ***Scan Preparation*** steps and start the scanning.

Step 29: After completing the scanning process (after a few minutes) start the *SCN Visualization Software*.

Step 30: Select the anti-phase component in SPL. Search for the frequency $f_{\text{break-up}}$ where the cone break-up occurs. This is the frequency where the SPL of the anti-phase component rises rapidly and is 30 dB below the total SPL.

$$SPL(f_{\text{break-up}}) - SPL_{\text{anti}}(f_{break-up}) = 30 \text{ dB}$$

Step 31: Select the total component in AAL. Search for the natural frequencies where the AAL shows destinct maxima. Determine the modal loss factor. Does the material provides optimal damping for the mode? View the mode of vibration. Which component (surround, cone, dust cap) contibutes significantly to the total modal loss factor?

7.3 Performing a Normal Explore Scan

Step 32: Repeat Step 23: - Step 26: give it name “**explore scan.ksp**”

Step 33: Select in *Preset* ***Manual Grid*** to customize the scanning grid.

Step 34: Choose the *Circular* ***Scan Area,*** enter the ***Radius*** of your driver and adapt the regular spacing of ***Radius Steps*** and ***Angle Steps***.

Step 35: Follow the ***Scan Preparation*** steps.

Step 36: After the scanning view the results of the measurement using the analysis software.

Step 37: Compare the SPL response on-axis in the measurement **profile scan.ksp** with the corresponding SPL curve measured in the **explore scan.ksp.** Explain the causes for the differences.

Step 38: Investigate the influence of the grids on the measurement of the circumferential modes of the loudspeaker.

Select the quadrature component in AAL. Search for the frequency f_{rock} where the first maximum in AAL quadrature component indicates a rocking mode. Is the difference $AAL_{rock}(f_{rock}) = AAL_{quad} - AAL_{in}$ larger than -5 dB?

Step 39: Start the *Sound Power Calculation* under the menu TOOLs. View the directivity index and search for frequency f_{6dB} where the *DI* equals 6 dB.

Step 40: Start the S_D Calculation under the menu TOOLs. Set the cursor at the voice coil position and read the the S_D-value.

8 Further Literature

User Manual for the KLIPPEL R&D SYSTEM – SCN Vibrometer

Specification C5 Scanning Vibrameter (SCN):

http://www.klippel.de/fileadmin/klippel/Bilder/Our_Products/R-D_System/PDF/C5_SCN_Scanning_Vibrometer.pdf

Poster Loudspeaker Cone Vibration:

http://www.klippel.de/fileadmin/_migrated/content_uploads/KLIPPEL_Cone_Vibration_Poster_01.pdf

Poster Loudspeaker Sound Radiation:

http://www.klippel.de/fileadmin/_migrated/content_uploads/KLIPPEL_Sound_Radiation_Poster_01.pdf

Application Note AN31 Cone Vibration and Radiation Diagnostics:

http://www.klippel.de/fileadmin/_migrated/content_uploads/AN_31_Cone_Vibration_and_Radiation_Diagnostics.pdf

Paper *Distributed Mechanical Parameters Describing Vibration and Sound Radiation of Loudspeaker Drive Units*:

http://www.klippel.de/fileadmin/_migrated/content_uploads/Klippel__Schlechter__Distributed_parameter.pdf

Paper *Visualization and Analysis of Loudspeaker Vibrations*:

http://www.klippel.de/fileadmin/_migrated/content_uploads/Visualization_and_Analysis_of_Loudspeaker_Vibration_01.pdf