FEATURES

- Identifies linear transducer model (Thiele / Small parameters)
- Measures suspension creep
- Parameter fitting based on impedance
- Parameter fitting based on displacement (optional)
- Single-step measurement with laser sensor
- Two-step measurement with additional mass or test enclosure
- Logarithmically spaced multi-tone excitation
- Measurements at low and high amplitudes
- Monitors ratio signal to noise + distortion (SNR+D) and noise floor
- Automatic validity check
- High reliability and reproducibility
- Fast measurements

The LPM module of the KLIPPEL Analyzer System is dedicated to identifying the electrical and mechanical small signal parameters of electro-dynamical transducers with high accuracy. It is based on the electrical impedance by measuring the voltage and current at the speaker terminals. Enhanced by an optional laser displacement sensor, the identification does not require a second measurement and thus avoids common problems of the traditional two-step methods (e.g. added mass). An additional benefit of the displacement measurement is the identification the suspension creep parameters, resulting in better accuracy of the loudspeaker model at low frequencies. The LPM provides tools to identify and avoid typical problems such as poor signal to noise ratio and malfunction due to nonlinear effects of the driver or amplifier limiting.

Content

1 Linear Modeling of the Transducer .............................................................. 2
2 Measurement Technique ................................................................................ 3
3 Ensuring Validity of the Results ..................................................................... 5
4 Import Parameter ........................................................................................... 5
5 Results ............................................................................................................ 6
1 Linear Modeling of the Transducer

Principle
The transducers considered here have a moving-coil assembly performing an
electro-dynamical conversion of the electrical quantities (current and voltage)
into mechanical quantities (velocity and force) and vice versa.

Equivalent Circuit
The lumped-parameter model shown above is valid at low frequencies where
the geometrical dimensions of the transducer are small in comparison to the
wave length. In this case the mechanical system may be represented by a moving
mass $M_{ms}$, a compliance $C_{ms}(f)$ and a mechanical resistance $R_{ms}$. The force factor
$B_l$ couples the mechanical with the electrical side of the transducer. The electrical
impedance is modeled by the electrical resistance $R_e$ and additional elements
$L_e, L_2$ and $R_2$ that describe the para-inductance and losses due to eddy currents.
It is also assumed that the amplitude of all state variables is sufficiently low to
neglect parameter variations caused by thermal and nonlinear mechanisms.

Suspension Creep
After applying a constant force to a loudspeaker suspension, the voice coil dis-
placement slowly varies and will find the equilibrium after a few seconds (creep).
This effect also affects the dynamic behavior and is visible in the transfer func-
tion $H_x(f)$ between voltage $U(f)$ and displacement $X(f)$ as shown below.

Below the resonance frequency $f_s$ there is a significant difference between the
magnitude of the measured response of $H_x(f)$ and the predicted response using
the traditional model.
To consider the creep effect the constant parameter compliance $C_{ms}$ is replaced
by the dynamic transfer function [1]:

$$C_{ms}(f) = C_{ms} \left[ 1 - \lambda \log_{10} \left( \frac{f}{f_s} \right) \right]$$

where $C_m$ is the linear compliance and $f_s$ is the driver resonance frequency.
There is a straight forward interpretation of the creep factor $\lambda$. The quantity
$\lambda \cdot 100\%$ indicates the decrease of the compliance $C_m$ in percent at low frequencies. For a frequency one decade below the resonance frequency $f_s$ the compliance $C_{ms}$ is decreased by $\lambda \cdot 100\%$.

include suspension creep. J. Audio Eng. Soc., Vol. 41, No. 1 / 2, 1993
Operating Condition

The Linear Parameter Measurement can be applied to drivers operated in free air or mounted in a sealed enclosure. An additional mass may be applied to the moving assembly of the transducer.

2 Measurement Technique

**Principle**

![Diagram of measurement setup]

The parameters of the linear transducer model are identified by measuring the electrical voltage $U(t)$ and current $I(t)$ at the transducer terminals. The linear parameters are identified by fitting the model to the measured impedance curve over the full frequency range.

**Minimal Setup**

- Distortion Analyzer (DA) or KLIPPEL Analyzer 3 (KA3 (A)LSX)
- Power amplifier or KA3 Amplifier Card
- Laser displacement sensor (optional)
- PC

**Excitation Signal**

The stimulus used during the measurement is a sparse multi-tone complex spaced logarithmically over frequency. This signal is optimal for the parameter identification at small amplitudes because the transducer is only excited at frequencies of interest.

The user may specify the amplitude and the frequency range covered by the tones and their distance (relative resolution). Furthermore, either the voltage at the output connector (OUT 1) or the voltage at the terminals of the speaker connected to output SPEAKER 1 (SPEAKER 2) may be specified. In the latter case the amplifier gain is determined at 750 Hz without load prior to the main measurement and the excitation level is adjusted accordingly. Also, the amplifier low frequency roll-off is determined and compensated for the two lowest frequency lines.

**Acquisition**

The state variables are acquired at sample rates up to 48 kHz. Optionally, averaging of the periodically measured time signals improves the signal to noise ratio.

**Spectral Analysis**

All of the measured time signals are subject to an FFT analysis. The resulting spectra show the fundamental response of the sparse multi-tone signal as well as the distortion generated by the transducer or amplifier and residual measurement noise.
### Parameter Estimation
All points of the measured impedance response are used for the identification of the electrical parameters, the resonance frequency and for the loss factors of the mechanical system. The estimated response (bold line) based on the identified model is displayed together with the measured response (thin line) to show the quality of the fitting.

![Magnitude of electric impedance Z(f)](image1)

### Using Added Mass or Test Enclosure
The Linear Parameter Measurement module supports the traditional two step techniques for the estimation of the mechanical parameters. They require a second (perturbed) measurement where the transducer is either mounted in a test enclosure or an additional mass is attached to it.

### Optional Laser Sensor
Both perturbation techniques are time consuming and the accuracy of the results may be impaired by leakage of the enclosure and problems due to the attachment of the mass. There are also transducers where neither of the techniques can be applied.

A laser sensor based on optical triangulation may be used instead to measure voice coil displacement directly.

The measured transfer function $H_x(f)$ between terminal voltage $U(f)$ and displacement $x(t)$ is used to estimate the mechanical parameters. Considering the creep effect at low frequencies gives a good agreement between measured response (thin curve) and the modeled response (bold line).

![Magnitude of transfer function Hx(f)= x(f)/U(f)](image2)

### Acoustical Environment
The influence of the room acoustics on the driver parameters may be neglected for a normal room size (volume > 30 m$^3$) and a distance of at least 1 m to the walls.

### Sound Pressure Response
Optionally, a microphone may be connected to the analyzer hardware and the radiated sound pressure signal may be measured simultaneously. The sparse multi-tone complex allows to measure the speaker distortion. This way a unique fingerprint of the speaker is obtained. Furthermore, the symptoms of driver non-linearities can be identified directly.
In the example above the speaker produces substantial distortion which exceed 10% at all frequencies for high excitation levels (large signal domain). This kind of distortion are produced by motor nonlinearities whereas stiffness distortion are restricted to low frequencies and inductance and Doppler distortion increase by 6 dB toward higher frequencies.

3 Ensuring Validity of the Results

Principle

The multi-tone complex used as excitation stimulus makes it possible to measure the fundamental components, signal distortion and the noise level simultaneously. This information is the basis for detecting a malfunction operation on-line and to give warnings if amplifier and transducer are not connected properly.

Amplifier Check

A low signal to noise ratio of the voltage signal at the terminals indicates that the gain of the amplifier is too low. A humming component (50 / 60 Hz) due to a ground loop can also be found easily.

The signal to distortion ratio shows a malfunction operation of the amplifier (such as limiting). In the example below the distortion generated by the power amplifier are 50 dB below the fundamental components and 25 dB above noise floor.

Small Signal Domain

If the signal to noise ratio in the measured current signal is too small then the number of averages has to be increased.

If the signal to distortion ratio in the measured current signal is too small then the driver behaves nonlinear and the linear model becomes invalid.

4 Import Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective area of the driver diaphragm</td>
<td>$S_d$</td>
<td>0.01</td>
<td>10000</td>
<td>cm$^2$</td>
<td></td>
</tr>
<tr>
<td>Voice coil resistance at DC (optional)</td>
<td>$R_e$</td>
<td>0.1</td>
<td></td>
<td>Ω</td>
<td></td>
</tr>
<tr>
<td>Force factor (optional)</td>
<td>$Bl$</td>
<td>0.01</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Moving mass (optional)</td>
<td>$M_{ms}$</td>
<td>0.1</td>
<td></td>
<td>g</td>
<td></td>
</tr>
</tbody>
</table>
Identification

Method

- using laser displacement meter, additional mass or using test enclosure
- optionally a shunt can be used to improve the signal to noise ratio for drivers with a low $Q_{ts}$

<table>
<thead>
<tr>
<th>Additional mass $M_{add}$</th>
<th>1</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of sealed enclosure $V_{box}$</td>
<td>0.5</td>
<td>dm³ (l)</td>
</tr>
<tr>
<td>Shunt resistance $R_{shunt}$</td>
<td>0</td>
<td>15</td>
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</table>

Stimulus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest frequency $f_{max}$</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>Reference frequency $f_{ref}$</td>
<td>0.19</td>
<td>25</td>
</tr>
<tr>
<td>Relative frequency resolution $\Delta f/f_{ref}$</td>
<td>1/99</td>
<td>1/24</td>
</tr>
<tr>
<td>Voltage at speaker terminals (power amplifier output voltage)</td>
<td>0</td>
<td>-200</td>
</tr>
<tr>
<td>Voltage at OUT 1 (power amplifier input voltage)</td>
<td>0</td>
<td>-200</td>
</tr>
</tbody>
</table>

Measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor terminal</td>
<td>Speaker 1 or Speaker 2</td>
<td></td>
</tr>
<tr>
<td>Number of averaging</td>
<td>1</td>
<td>16</td>
</tr>
</tbody>
</table>

5 Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC resistance of driver voice coil</td>
<td>$R_e$</td>
<td>Ω</td>
</tr>
<tr>
<td>Lumped elements of para-inductance</td>
<td>$L_e$</td>
<td>mH</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Ω</td>
<td></td>
</tr>
<tr>
<td>$L_2$</td>
<td>mH</td>
<td></td>
</tr>
<tr>
<td>Electrical resistance due to mechanical losses</td>
<td>$R_{ms}$</td>
<td>Ω</td>
</tr>
<tr>
<td>Electrical capacitance representing moving mass</td>
<td>$C_{mes}$</td>
<td>µF</td>
</tr>
<tr>
<td>Electric inductance representing driver compliance</td>
<td>$L_{ces}$</td>
<td>mH</td>
</tr>
<tr>
<td>Real part of voice coil impedance at $f_s$</td>
<td>$\Re{Z(f_s)}$</td>
<td>Ω</td>
</tr>
<tr>
<td>Mechanical mass of driver diaphragm assembly including air load and voice coil</td>
<td>$M_{ms}$</td>
<td>g</td>
</tr>
<tr>
<td>Mechanical resistance due to mechanical losses</td>
<td>$R_{ms}$</td>
<td>kg/s</td>
</tr>
<tr>
<td>Mechanical compliance of driver suspension</td>
<td>$C_{ms}$</td>
<td>mm/N</td>
</tr>
<tr>
<td>Creep factor</td>
<td>$\lambda$</td>
<td></td>
</tr>
<tr>
<td>Mechanical stiffness of driver suspension</td>
<td>$K_{ms}$</td>
<td>N/mm</td>
</tr>
<tr>
<td>Force factor at the rest position ($Bl$ product)</td>
<td>$Bl$</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Derived Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency of driver</td>
<td>$f_s$</td>
<td>Hz</td>
</tr>
<tr>
<td>Total Q-factor of driver considering $R_e$ and $R_{ms}$ only</td>
<td>$Q_{ts}$</td>
<td></td>
</tr>
<tr>
<td>Electrical Q-factor of driver in free air considering $R_e$ only</td>
<td>$Q_{es}$</td>
<td></td>
</tr>
<tr>
<td>Electrical Q-factor considering $\Re{Z(f_s)}$</td>
<td>$Q_{es}$</td>
<td></td>
</tr>
<tr>
<td>Total Q-factor considering all losses ($R_e$, $R_{ms}$, $\Re{Z(f_s)}$)</td>
<td>$Q_{tp}$</td>
<td></td>
</tr>
<tr>
<td>Mechanical Q-factor of driver in free air considering $R_{ms}$ only</td>
<td>$Q_{ms}$</td>
<td>%</td>
</tr>
<tr>
<td>Reference efficiency of electro-acoustical conversion ($2\pi$-radiation load)</td>
<td>$\eta_0$</td>
<td>dB</td>
</tr>
<tr>
<td>Characteristic sound pressure level</td>
<td>$L_m$</td>
<td></td>
</tr>
<tr>
<td>Equivalent air volume of suspension</td>
<td>$V_{as}$</td>
<td>dm³ (l)</td>
</tr>
</tbody>
</table>
**Linear Parameter Measurement (LPM)**

### Results

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency of driver in enclosure</td>
<td>$f_c$</td>
<td>Hz</td>
</tr>
<tr>
<td>Electrical Q-factor of driver in enclosure considering $R_e$ only</td>
<td>$Q_{e_c}$</td>
<td></td>
</tr>
<tr>
<td>Resonance frequency of driver with additional mass</td>
<td>$f_m$</td>
<td>Hz</td>
</tr>
</tbody>
</table>

### Time Signals

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform of voltage at transducer terminals</td>
<td>$U(t)$</td>
<td>V</td>
</tr>
<tr>
<td>Waveform of current at transducer terminals</td>
<td>$I(t)$</td>
<td>A</td>
</tr>
<tr>
<td>Waveform of sound pressure</td>
<td>$p(t)$</td>
<td>Pa</td>
</tr>
<tr>
<td>Waveform of displacement</td>
<td>$X(t)$</td>
<td>mm</td>
</tr>
</tbody>
</table>

### Spectra

<table>
<thead>
<tr>
<th>Spectra</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage spectrum</td>
<td>$U(f)$</td>
<td>dBu</td>
</tr>
<tr>
<td>Current spectrum</td>
<td>$I(f)$</td>
<td>dB</td>
</tr>
<tr>
<td>Sound pressure spectrum</td>
<td>$p(f)$</td>
<td>dBu</td>
</tr>
<tr>
<td>Displacement spectrum</td>
<td>$X(f)$</td>
<td>mm</td>
</tr>
<tr>
<td>Measured (laser/microphone) and fitted sound pressure level at 1W / 1m</td>
<td>$SPL$</td>
<td>dB</td>
</tr>
</tbody>
</table>

### Transfer Functions

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of measured and fitted electrical impedance $Z(f)$</td>
<td>$Z(f) = \frac{U(f)}{I(f)}$</td>
<td>Ω</td>
</tr>
<tr>
<td>Phase of measured and fitted electrical impedance $Z(f)$</td>
<td>$Z(f) = \frac{U(f)}{I(f)}$</td>
<td>rad</td>
</tr>
<tr>
<td>Magnitude of measured and estimated displacement transfer function</td>
<td>$H_x(f) = \frac{X(f)}{U(f)}$</td>
<td>mm/V</td>
</tr>
</tbody>
</table>

### States and Measurement Variables

<table>
<thead>
<tr>
<th>State</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak to peak value of voltage at terminals</td>
<td>$U_{pp}$</td>
<td>V</td>
</tr>
<tr>
<td>DC part of voltage signal</td>
<td>$U_{dc}$</td>
<td>V</td>
</tr>
<tr>
<td>AC part of voltage signal</td>
<td>$U_{ac}$</td>
<td>V</td>
</tr>
<tr>
<td>Digital headroom of voltage signal</td>
<td>$U_{head}$</td>
<td>dB</td>
</tr>
<tr>
<td>Ratio of signal to noise + distortion in voltage signal</td>
<td>$U_{SNR+D}$</td>
<td>dB</td>
</tr>
<tr>
<td>Frequency of noise maximum in voltage signal</td>
<td>$f_{U_{noise}}$</td>
<td>Hz</td>
</tr>
<tr>
<td>Peak to peak value of current at terminals</td>
<td>$I_{pp}$</td>
<td>A</td>
</tr>
<tr>
<td>DC part of current signal</td>
<td>$I_{dc}$</td>
<td>A</td>
</tr>
<tr>
<td>AC part of current signal</td>
<td>$I_{ac}$</td>
<td>A</td>
</tr>
<tr>
<td>Digital headroom of current signal</td>
<td>$I_{head}$</td>
<td>dB</td>
</tr>
<tr>
<td>Ratio of signal to noise + distortion in current signal</td>
<td>$I_{SNR+D}$</td>
<td>dB</td>
</tr>
<tr>
<td>Frequency of noise maximum in current signal</td>
<td>$f_{I_{noise}}$</td>
<td>Hz</td>
</tr>
<tr>
<td>Peak to peak value of displacement signal</td>
<td>$X_{pp}$</td>
<td>mm</td>
</tr>
<tr>
<td>DC part of displacement signal</td>
<td>$X_{dc}$</td>
<td>mm</td>
</tr>
<tr>
<td>AC part of displacement signal</td>
<td>$X_{ac}$</td>
<td>mm</td>
</tr>
<tr>
<td>Digital headroom of displacement signal</td>
<td>$X_{head}$</td>
<td>dB</td>
</tr>
<tr>
<td>Frequency of highest valid line in displacement signal</td>
<td>$f_{X_{cutoff}}$</td>
<td>Hz</td>
</tr>
<tr>
<td>Peak to peak value of microphone signal</td>
<td>$p_{pp}$</td>
<td>V</td>
</tr>
<tr>
<td>DC part of microphone signal</td>
<td>$p_{dc}$</td>
<td>V</td>
</tr>
<tr>
<td>AC part of microphone signal</td>
<td>$p_{ac}$</td>
<td>V</td>
</tr>
<tr>
<td>Digital headroom of microphone signal</td>
<td>$p_{head}$</td>
<td>dB</td>
</tr>
<tr>
<td>Ratio of signal to noise + distortion in microphone signal</td>
<td>$p_{SNR+D}$</td>
<td>dB</td>
</tr>
<tr>
<td>Frequency of noise maximum in microphone signal</td>
<td>$f_{p_{noise}}$</td>
<td>Hz</td>
</tr>
</tbody>
</table>

Find explanations for symbols at:

[http://www.klippel.de/know-how/literature.html](http://www.klippel.de/know-how/literature.html)

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