Measurement of Nonlinear Thermal Parameters   **AN 19**

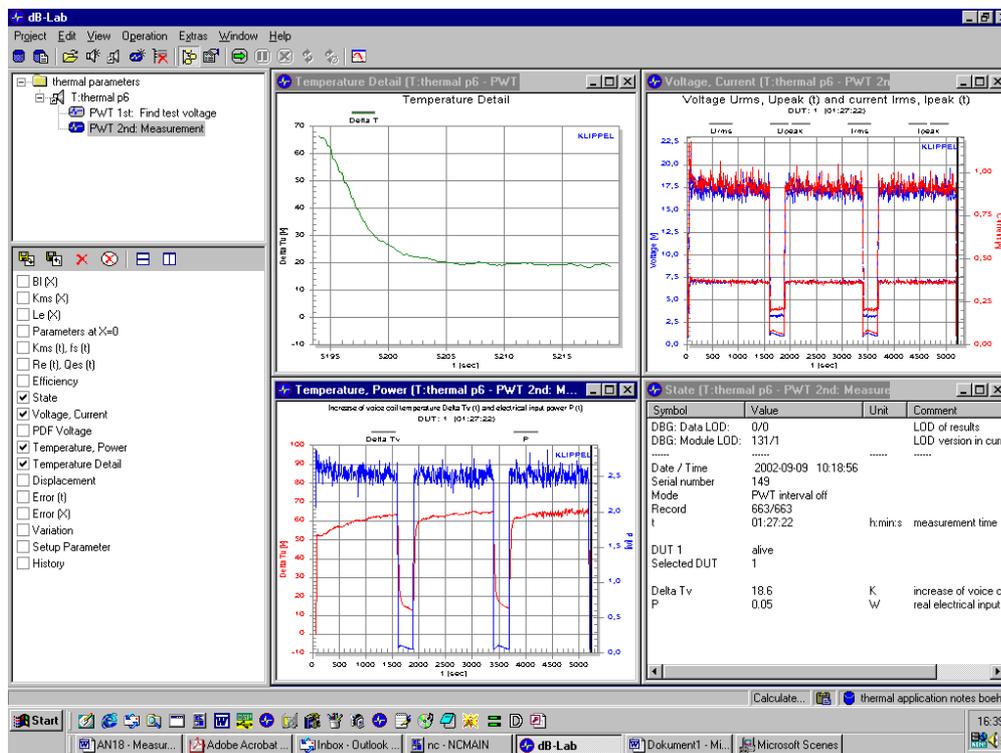Application Note to the KLIPPEL R&D SYSTEM

Traditional modeling describes the heat flow in loudspeakers by an equivalent circuit using integrators with constant parameters (Application Note AN 18). This simple model fails in describing the air convection cooling which becomes an effective cooling mechanism if the velocity of the coil and/or the velocity of the forced air in the gap becomes high. Eddy currents generated in the conductive material close to the voice coil directly heat the pole piece and the shorting ring and generates a bypass for the heat. These effects are considered in an extended thermal model. This application note presents a simple measurement technique to identify the convection parameter r_v, the power splitting parameter α and the other thermal parameters.
Note: This AN 19 describes a manual process to determine the thermal model that can be done with PWT Power Test. LSI Woofer and LSI Tweeter can identify this thermal model in an automatic measurement.

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updated April 4, 2012

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Thermal Model
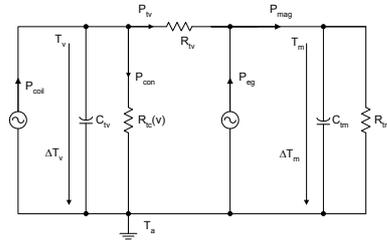
The equivalent circuit presented above is used for modeling the thermal behaviors of transducers. This simple model represents the complex temperature field by the mean temperature T_v of the voice coil and the mean temperature T_M of the magnet, pole pieces and frame. This model considers multiple paths of the heat flow. The voice coil is heated by the power P_{coil}

$$P_{coil} = P_{Re} + \alpha \, P_{R2} \tag{1}$$

is the sum of the power dissipated in resistance R_e and a fraction of the power (according to the distribution factor α)

$$P_{R2} = R_2 i_2^{\,2} \tag{2}$$

dissipated by current

$$i_2 = \frac{i}{\sqrt{1 + \left(\dfrac{R_2}{L_2\,2\pi f}\right)^2}}. \tag{3}$$

The main part of the heat goes as power P_{tv} via resistance R_{tv} to the pole pieces, magnet and frame. Finally the heat is transferred via resistance R_{tm} to the ambience. Due to convection cooling the power P_{con} is transferred directly into the ambience. The resistance $R_{tc}(v)$

$$R_{tc}(v) = \frac{1}{v_{rms} r_v} \tag{4}$$

depending on the voice coil velocity v is the limiting factor in convection cooling. The power P_{eg} represents the eddy currents in the pole piece and the short cut ring also bypasses the coil. The thermal capacity C_{tv} represents the thermal dynamics of the voice coil and the capacity C_{tm} represent the magnet and frame.
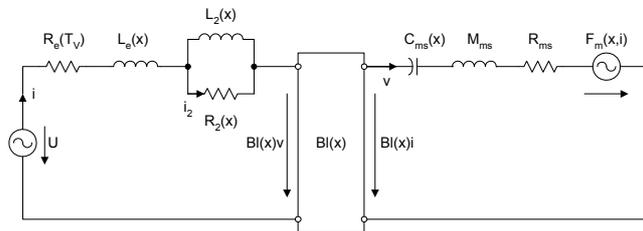
The equivalent circuit presented above is used for modeling the electro-mechanical system of the driver. The power dissipated in resistance R_2 represents loss due to the eddy currents.

Difference to   The traditional thermal modeling neglects the convection cooling and the direct heat

Traditional Modeling	transfer due to eddy currents. Using a signal generating high voice coil velocity and eddy currents then most of the power will bypass the voice coil and significantly lower values of the parameters R_{TV} and R_{TM} will be measured. Thus the parameters C_{TV}, R_{TV}, C_{TM}, R_{TM} of the traditional modeling have to be considered as effective parameters which depend on the spectral properties of the excitation signal.
Why coping with Convection Cooling ?	Air convection cooling is a mechanism transfer the heat to the environment directly and bypass. Enhancing this effect by special driver design (forced air convection cooling) keeps the voice temperature at a lower level and makes more acoustical output possible.
Bypass Factor	The bypass power factor $$\gamma = \frac{P_{con} + P_{eg}}{P_{Re} + P_{R2}} \qquad (5)$$ describes the ratio of power which is directly transferred to the magnet and the ambience but does not contribute to the heating of the coil. Increasing the bypass factor γ will improve the power handling of the speaker.
Principle of Measurement	Then three long term power tests are performed using a single tone as stimulus, which is adjusted to the following frequencies: $f_1 \approx 10\ f_s$ to measure voice coil and magnet parameters $f_2 \gg f_1$ to measure direct heat transfer $f_3 \approx 1.5\ f_s$ to measure convection parameters The single tone f_1 in the first power test is set in the middle of the frequency band where the air convection cooling is negligible. The tone f_2 in the second test is set as high as possible to measure the largest effect of the direct heat transfer due to eddy currents. The tone f_3 in the last test is set close but not directly at the resonance frequency f_s to supply sufficient power to the driver. The stimulus is switched by a cycle scheme (t_{on}=25 min, t_{off}= 5 min). The amplitude of the stimulus is adjusted to the particular driver to get sufficient heating while avoiding thermal or mechanical damage. The duration of the power test should be sufficiently long (> 4 τ_m) to have the magnet and frame in thermal equilibrium. During the test the rms-value of the input current $i_{rms}(t)$ and voice coil resistance $R_e(t)$ is monitored and recorded with sufficient temporal resolution. For the third stimulus $f=f_3$ the rms-value $x_{rms}(f_3)$ of the voice coil displacement is also measured.

Performing the Measurement

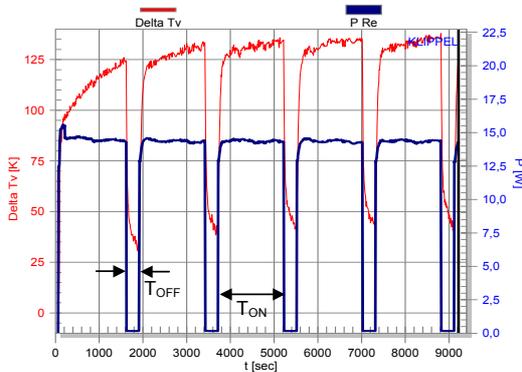| *Requirements*	The following hardware and software is required • Power Test Monitor PM 8 (or Distortion Analyzer) • PC • Software modules (PWT, DIS, LPM, dB-Lab) • Sinusoidal Generator • Laser Sensor Head • Power Amplifier (set gain to maximum)
Setup	Connect the output of the sinusoidal generator to the input IN1 at the rear side of the DA. Connect the terminals of the driver with SPEAKER 1. Switch the power amplifier between OUT1 and connector AMPLIFIER. Connect the laser sensor head to the connector LASER and adjust the laser beam to a white dot on the diaphragm.
Preparation	1. Open dB-Lab 2. Create a new object DRIVER based on the template **Thermal Parameters AN 19**

Measurement	1. Start the measurement "**LPM: Linear Parameters**". Read the resonance frequency f_s and the lumped parameter R_e, L_e, L_2. 2. Set the sinusoidal generator at $f_1 = 10*f_s$. Attenuate the output amplitude. 3. Start the measurement "**PWT: Thermal Measurement**". After entering the ON-Mode adjust the output gain of the sinusoidal generator to have an increase of the voice coil temperature of about 80 Kelvin. 4. After 10 minutes open the property page "**Method**". Select the **fast speed temperature** monitoring to be able to measure the cooling characteristic at high resolution. Under **Temperature Window** press the button **Start** to activate the next detailed temperature monitoring. 5. One hours after starting the measurement set the frequency of the tone to $f_2 = 100$ f_s *(< 20 kHz)* . Adjust the amplitude of the signal to have an increase of the voice coil temperature of 80 Kelvin while keeping the voice coil displacement in the acceptable range. 6. Two hours after starting the measurement set the frequency to $f_3 = 1.5\ f_s$. Adjust the amplitude of the tone to have an increase of the voice coil temperature of 80 Kelvin. 7. Finish the measurement three hours after starting the measurement. 8. Open the result window "**voltage, current**" and read the rms voltage $U_{rms}(f_3)$ at the end of the last ON-phase using the tone $f_3 = 1.5\ f_s$ by using the cursor. 9. Open the property page of the measurement "**DIS: Displacement at 1.5 fs**". Enter the frequency $f_1=1.5\ fs$ and the voltage $U_{end}=U_{rms}(f_3)$ for the first tone. After performing the measurement open the result window **Table Signal Characteristic** and read the rms displacement X AC for $U_{rms}(f_3)$. 10. If the DIS module is not available then do the following steps: Connect the sinusoidal generator output with the amplifier input. Select the frequency $f_3=1.5\ f_s$ and generate the voltage $U_{rms}(f_3)$ at the loudspeaker terminals. Start the program Displacement Meter at the Distortion Analyzer 1 and read the peak to peak displacement X_{pp}. Calculate the rms displacement $x_{rms}=0.35\ X_{pp}$.

Reading Values from Power test

|	
Termperatures $\Delta T_{on}(f)$, **currents $i_{rms}(f)$**	1. Open the result window **Temperature Detail**; **Temperature, Power**; **State** and **Voltage, Current**. *Voice coil temperature T_V (thin line) and Power P_{Re} (thick line) during the cycled $f_1=1\ kHz$ tone versus time.* 2. Read the maximal increase of voice coil temperature $\Delta T_{on}(f)$ out of the window **Temperature, Power** and the rms value of the input current $i_{rms}(f)$ at the end of the last ON-phase t_{s_off} for $f = f_1$, f_2 and f_3 out of the window **Voltage, Current** by using the *cursor*.

Termperatures
ΔT_off(f)

3. Read the increase of the voice coil temperature $\Delta T_{off}(f)$ after the coil is in thermal equilibrium in during the **OFF-phase** out of the window **Temperature Power**. The short time constant of the voice coil τ_v causes the rapid decay at the beginning of the OFF-phase. The larger time constant τ_m of the magnet/frame structure causes an additional decay starting at later times. To separate both processes, the early decay is approximated by a straight line and the crossing point with the minimal temperature in the OFF-phase gives the slope time t_{slope}. At approximately 5 times of t_{slope} when the voice coil is in thermal equilibrium read the temperature $\Delta T_{off}(f) = \Delta T_V(t_{s\_off} + 5t_{slope})$ for $f = f_1$, f_2 and f_3.
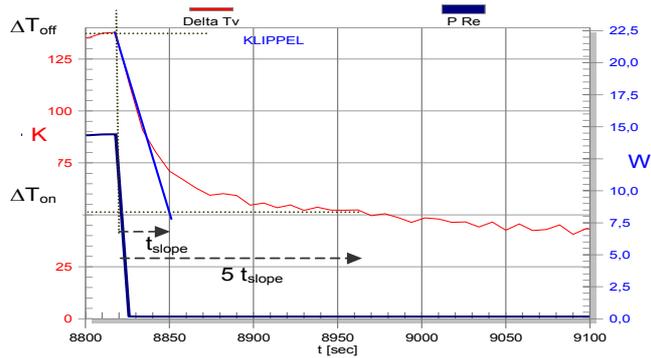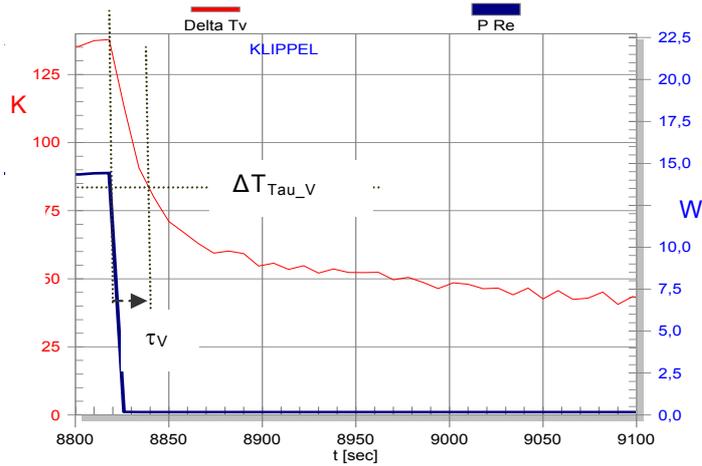
Reading temperature T_{off} in the cooling phase of the last cycle.

Time Constant τ_v

4. Consider the result of the power test using the tone $f_1=10f_s$ and calculate the threshold temperature

$$\Delta T_{tau\_v}(t_{tau\_v}) = \Delta T_{tv}(t_{s\_off} + \tau_{tv})$$
$$= 0.37 \ \Delta T_{on}(f_1) + 0.63 \ \Delta T_{off}(f_1)$$ (6)

at which the time constant of the voice coil is elapsed.

Reading the time constant τ_v in the cooling phase

5. Read the time t_{tau_v} in last OFF-phase during the power test with frequency f_1 when the temperature decayed to ΔT_{tau_v} the time constant of the voice coil is calculated by

$$\tau_v = t_{tau\_v} - t_{s\_off}$$ (7)

Time Constant τ_m

6. Calculate the temperature threshold ΔT_{tau_m} where the time constant of the magnet is elapsed

$$\Delta T_{tau\_m} = \Delta T_V(t_{start} + \tau_m) = \Delta T_{on} - 0.37 * \Delta T_{off} .$$ (8)

7. Read the starting time t_{start} and the time t_{tau_m} when the voice coil temperature is equal to ΔT_{tau_m} out of the window **Temperature Details** and calculate

$$\tau_m = t_{tau\_m} - t_{start}$$ (9)
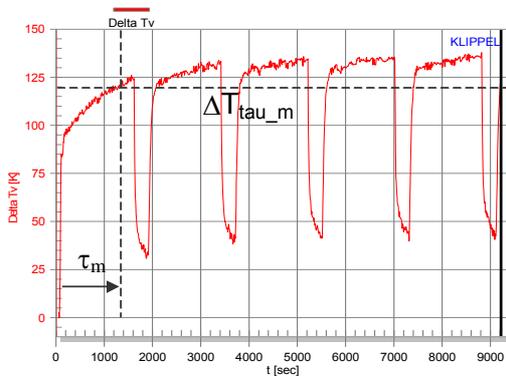
Reading the time constant τ_m of the magnet.

Parameter Calculation

Excel-Sheet	Use the Excel-Sheet "**calculation_thermal_parameters.xls**" to calculate the thermal parameters. You have to enter the temperatures $\Delta T_{on}(f)$, $\Delta T_{off}(f)$ and the rms current $i_{rms}(f)$ for $f = f_1$, f_2 and f_3, rms value of the displacement $x_{rms}(f_3)$, resistance $R_e(T_A)$ at ambient temperature, the lumped parameters of the voice coil L_e, R_2, L_2 and the conductivity parameter of the voice coil material and the time constants τ_{tv} and τ_{tm}.
Calculation "by hand"	If the Excel-Sheet is not available you may perform the following calculation by hand

1. Power splitting coefficient

$$\alpha = -\frac{\varepsilon\, P_{\mathrm{Re}}(f_2) - P_{\mathrm{Re}}(f_1)}{\varepsilon\, P_{R2}(f_2) - P_{R2}(f_1)} \tag{10}$$

using the power

$$P_{\mathrm{Re}} = R_e(T_v)i^2 \tag{11}$$

dissipated in the resistor R_e and the power

$$P_{R2} = \frac{R_2 i^2}{1 + \left(\dfrac{R_2}{L_2 2\pi f}\right)^2} \tag{12}$$

dissipated in the resistor R_2 and the temperature ratio

$$\varepsilon = \frac{\Delta T_{on}(f_1) - \Delta T_{off}(f_1)}{\Delta T_{on}(f_2) - \Delta T_{off}(f_2)} \tag{13}$$

measured at frequencies f_1 and f_2.

2. Thermal resistance of the magnet/frame structure

$$R_{tm} = \frac{\Delta T_{off}(f_1)}{P_{\mathrm{Re}}(f_1) + P_{R2}(f_1)} \frac{t_{on} + t_{off}}{t_{on}} \tag{14}$$

considering the long term mean power averaged over one cycle

3. Thermal resistance of the voice coil

$$R_{tv} = \frac{\Delta T_{on}(f_1) - \Delta T_{off}(f_1)}{P_{\mathrm{Re}}(f_1) + \alpha P_{R2}(f_1)} \tag{15}$$

considering both power sources

4. Thermal capacity of the voice coil

$$C_{TV} = \frac{\tau_{tv}}{R_{tv}} \tag{16}$$

5. Thermal capacity of the magnet structure

$$C_{TM} = \frac{\tau_{tm}}{R_{tm}} . \tag{17}$$

6. Thermal resistance due to convection cooling

$$R_{tc} = \frac{1}{\dfrac{P_{\mathrm{Re}}(f_3)}{\Delta T_{on}(f_3)} - \dfrac{1}{R_{tv} + R_{tm}}} \tag{18}$$

7. Convection cooling parameter

$$r_c = \frac{1}{x_{rms}\, 2\pi f_3 R_{tc}} \tag{19}$$

Setup Parameters for the Template Measurement

Template	Create a new Object, using the object template **Thermal Parameters AN 19** in dB-Lab. If this database is not available you may generate a generate an object **Thermal Parameters AN 19** based on the general PWT module. You may also modify the setup parameters according to your needs.
LPM Linear Parameters	1. Generate a measurement based on the general LPM measurement. Set maximal frequency F_{max} 5 kHz.
PWT Thermal Measurement	1. Generate a measurement based on the general **PWT** measurement. Open the PP INFO and call it "**Thermal Measurement**". Open the PP STIMULUS. Select **bypass** mode.
	2. Open the PP **CYCLES** and set the ON-Interval T_{ON}= 25 min and the OFF-Interval T_{OFF}= 5 min. Set the total measurement time T_{TOT}= 3 h and a regular sampling after T_{UPD}= 8s.
	3. Open the PP **METHOD** and select **Temperature** mode and set Number of DUTs to 1. Use **slow** temperature monitoring at the beginning of the measurement. For the result Window "Temperature Detail" disable the **auto**matic start but enable the checkbox SYNC with PWT ON/OFF. Select **Edit...,** open **Manual** and set the pilot tone frequency at $f_p < f_s/10$.
	4. Open the PP **FAILURE** and set the minimal resistance R_{min} to 10 % and the maximal resistance R_{max} to 150 % or other value.
DIS Displacement at 1.5 fs	5. Generate a measurement based on the general DIS measurement. Open the PP INFO and call it "**DIS: Displacement at 1.5 fs**". Open the PP STIMULUS. Select the mode **Harmonics**. Enable the voltage sweep set starting voltage U_{start}= 0.001. Select voltage measured at terminal **Speaker 1**. Disable frequency sweep. Set maximal order of distortion analysis to 4. Set additional excitation before starting measurement to 0.5 s.
	6. Select the result windows **Fundamental** and **Table signal characteristics** as default windows.
	7. Open the PP Display and select the displayed signal **Displacement**

Glossary of Symbols

i	input current at terminals
u	voltage at terminals
x	voice coil displacement
v	velocity of voice coil
i_2	current in resistance R_2 representing losses due to eddy currents
P_{Re}	power dissipated in R_e
P_{R2}	power dissipated in R_2
P_{coil}	total power transferred to voice coil
P_{mag}	total power transferred to magnet
P_{eg}	power supplied to magnet due to eddy currents
P_{con}	power supplied to ambience due to convection cooling
T_v	temperature of the voice coil
T_m	temperature of the magnet structure
ΔT_v	increase of voice coil temperature
ΔT_m	increase of the temperature of magnet structure and frame
T_a	temperature of the cold transducer (ambient temperature)
γ	bypass factor (fraction of the power that bypasses the coil)

Driver Parameters		
	$R_e(T_v)$	electrical voice coil resistance at DC depending on voice coil temperature
	$R_e(T_a)$	electrical voice coil resistance at DC of cold coil
	L_e	voice coil inductance at low frequencies
	L_2	para-inductance at high frequencies
	R_2	resistance due to eddy currents
	f_s	resonance frequency of the mechanical system

Thermal parameters		
	R_{tv}	thermal resistance of path from coil to magnet structure due to conduction
	R_{tm}	thermal resistance of magnet structure to ambient air
	C_{tv}	thermal capacitance of voice coil and nearby surroundings
	C_{tm}	thermal capacitance of magnet structure
	$R_{tc}(v)$	thermal resistance of path from coil to air in the gap due to convection cooling
	α	factor describing the distribution of heat caused by eddy currents on voice coil and magnet
	r_v	convection cooling parameter considering the cone velocity
	δ	thermal conductivity parameter (δ=0.039 for copper)
	τ_v	time constant of the voice coil
	τ_m	time constant of the magnet frame

Variables used in power test	ΔT_{on}	maximal voice coil temperature ΔT_v during the ON-phase of the power test cycle
	ΔT_{off}	voice coil temperature ΔT_v measured in the OFF-phase of the power test cycle
	t_{on}	duration of the ON-phase of the power test cycle
	t_{off}	duration of the OFF-phase of the power test cycle
	t_{tau_v}	time in the last off-phase when temperature decayed to ΔT_{tau_v}
	t_{s_off}	time when the last off-phase starts
	t_{start}	starting time of the measurement
	t_{tau_v}	time when the temperature is equal to ΔT_{tau_m}
	ΔT_{tau_m}	threshold temperature used for assessing τ_m
	ΔT_{tau_v}	threshold temperature used for assessing τ_v

More Information

Literature	Klippel, Nonlinear Modeling of the Heat Transfer in Loudspeakers , presented at the 114th Convention of the Audio Eng. Soc., Amsterdam, The Netherlands, 2003 March 22–25
Related Application Notes	"Thermal Parameter Measurement", Application Note 18
Related Specification	"S1- Large Signal Identification (LSI) ", Software of the Klippel R&D System
Software	User Manual for the KLIPPEL R&D SYSTEM.

Kommentar [W1]: preprint number should be added

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