Acceleration Measurement using a AN74 Laser Displacement Sensor

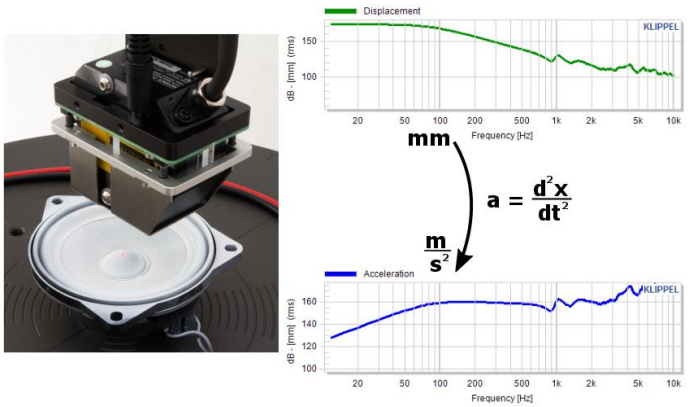
KLIPPEL ANALYZER SYSTEM (Document Revision 1.3)

FEATURES

- Contactless acceleration measurements
- Applicable to micro-speakers and headphones
- Frequency response
- No additional resonances due to sensor mounting

APPLICATION

- Small speakers
- Shakers



DESCRIPTION

Testing acceleration of transducers and shakers is a common application in the audio industry. Normally small acceleration sensors will be attached to the device under test (DUT) for measuring the acceleration directly. But those sensors need to be glued or screwed to the DUT which is not appropriate to small speakers with low moving mass compared to the sensor weight. This is why a contactless measurement of the acceleration would be useful instead of attaching an additional sensor to the DUT's diaphragm.

This application note explains how to use the *TRF* Transfer Function [1] module and a laser displacement sensor for measuring acceleration. This will be done using a woofer as an example to directly compare the acceleration result of a direct measurement with the calculation from the measured displacement. Problems and particularities will be discussed.

CONTENT

1 Requirements 2

2 Measurement 3

3 Comparison with acceleration sensor 7

4 Measurement at higher frequencies 8

5 Further information 10

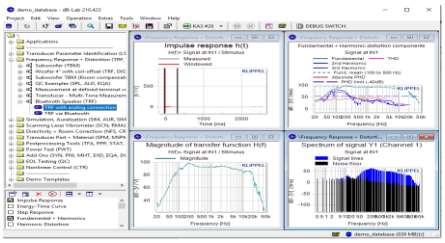
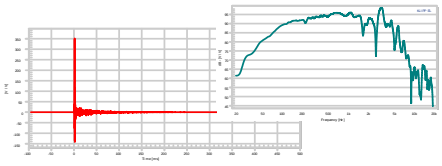
6 References 12

1 Requirements

1.1 Hardware

Klippel Analyzer (KA3 or DA2)	Hardware platform for the measurement modules performing the signal generation, acquisition and digital signal processing. [4]	
Laser displacement sensor	Due to the weak displacement at higher frequencies a laser sensor with high resolution (low noise floor) is required. [2]	

1.2 Software

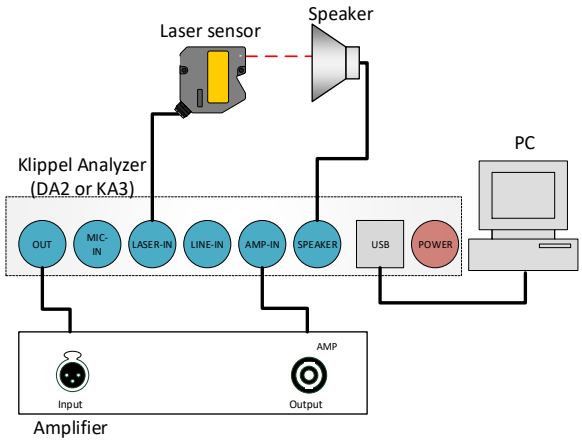
dB-Lab version 206 or higher	Frame software of the Klippel Analyzer system.	
Transfer Function Module ***TRF/ TRF Pro***	The Transfer Function Module (*TRF*) is a dedicated software module for the measurement of the transfer behavior of a loudspeaker or system. [1]	

2 Measurement

2.1 Device under test (DUT)

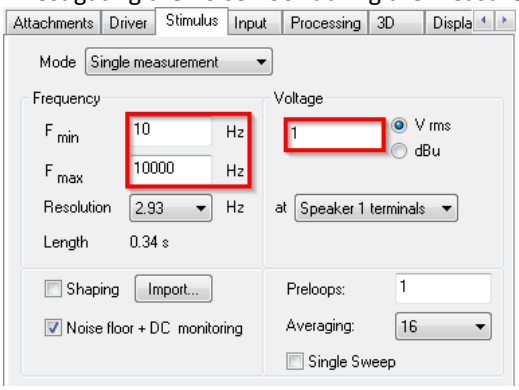
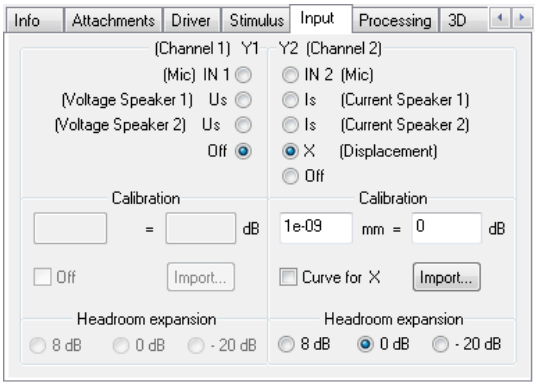
Woofer	The device under test for this example is a 5 inch woofer. Its moving mass is relatively high compared to the mass of the acceleration sensor used for comparison.

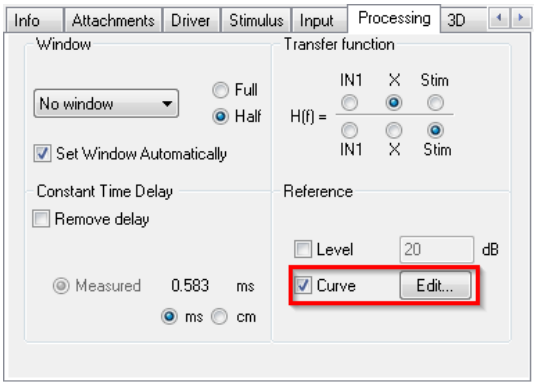
2.2 Measurement setup

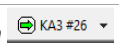
Calibrate your laser sensor	Before measuring with your laser displacement sensor you have to calibrate it. You can use either the calibration target at the Pro Driver Stand, the Translation Stage or KLIPPEL SCN hardware for the laser calibration. Please see the Hardware manual (go to menu “Help” -> “PDF Manuals” in dB-Lab) for further information about the laser calibration process for DA2 and KA3.
Connect hardware	

2.3 Performing measurement

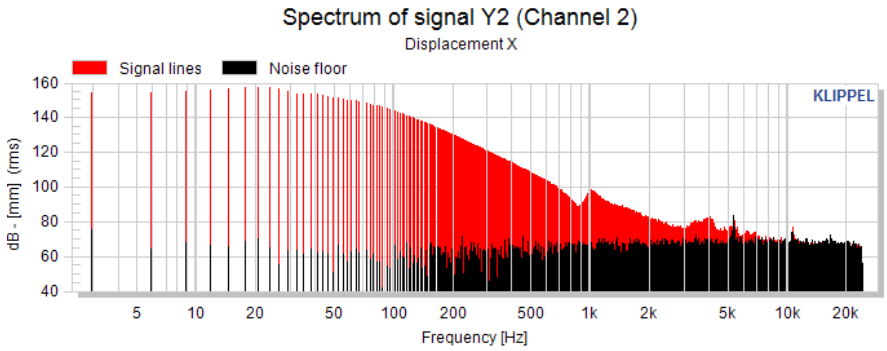
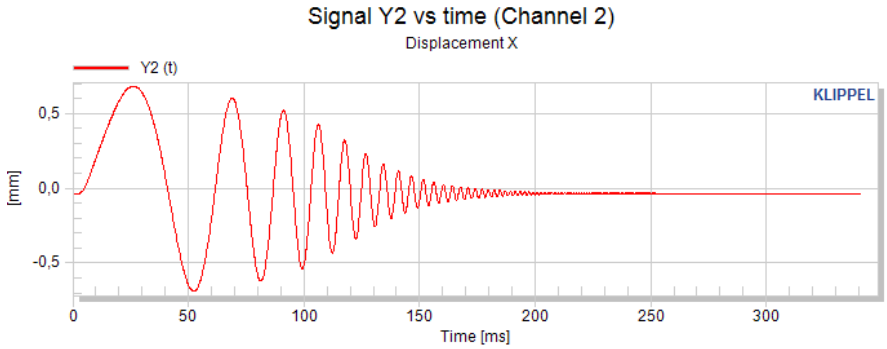
Template	The dB-Lab object template *Acceleration testing with laser* is provided with this application note or your KLIPPEL software. Create your own test based on this template. This object template contains a *TRF* operation for the measurement and an additional *PPP* operation for further post-processing if required.

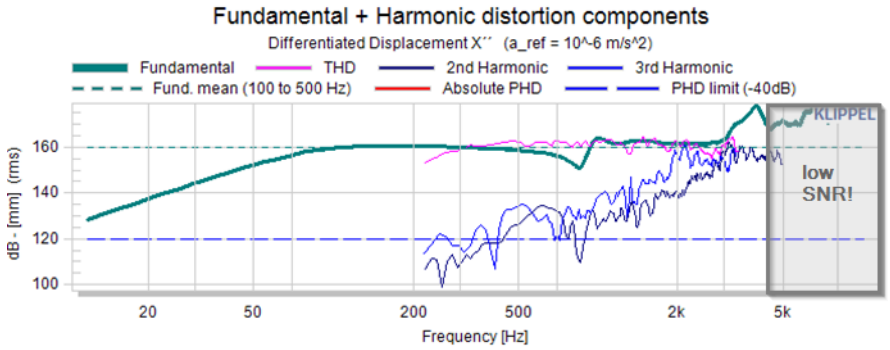
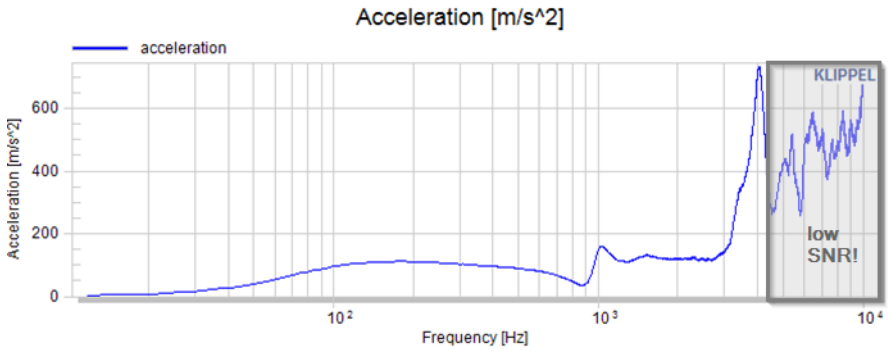
Stimulus Settings	Open the ***Property Page*** of the *TRF* Operation and select the ***Stimulus*** Tab. Here you may change the frequency range or stimulus level according to your needs and transducer type. It is recommended using the option ***Noise floor + DC monitoring*** for investigating the noise floor during the measurement. 
Input Settings	Only the displacement input (X) is used for this measurement. According to standard ISO 1683 the reference displacement (0 dB) is defined as 10^{-12} m. Thus, the calibration inside the *TRF* is set to 10^{-9} mm = 0 dB. 

Processing	For calculating the acceleration from the measured displacement it is necessary to differentiate the displacement twice. This differentiation is done using the *Reference* curve which is defined as:
	`Curve = [`
	`1 88 180`
	`100000 -112 180];`
	 
	Find more background information about this reference curve in section 5.

Run the Measurement	After finishing the configuration, press the green arrow to ***run***  the operation.

2.4 Results

Spectum Y2(f)	Open the window ***Y2 (f) Spectrum***. In case you have enabled the *Noise Floor + DC monitoring* in the stimulus settings (always recommended), you will see the black lines of the measured noise floor and the red lines of the measured displacement in this chart. Please check that the distance between the highest black lines (noise) and the lowest red lines (signal) is at least 20 dB. If this difference is lower, you may duplicate the measurement operation and perform it again with higher stimulus voltage or higher number of averages. 
Displacement signal Y1 (t)	The ***Y1(t)*** window shows the measured time signal of the displacement measurement. This window is a good indicator to check if the speaker is within its displacement limits. 

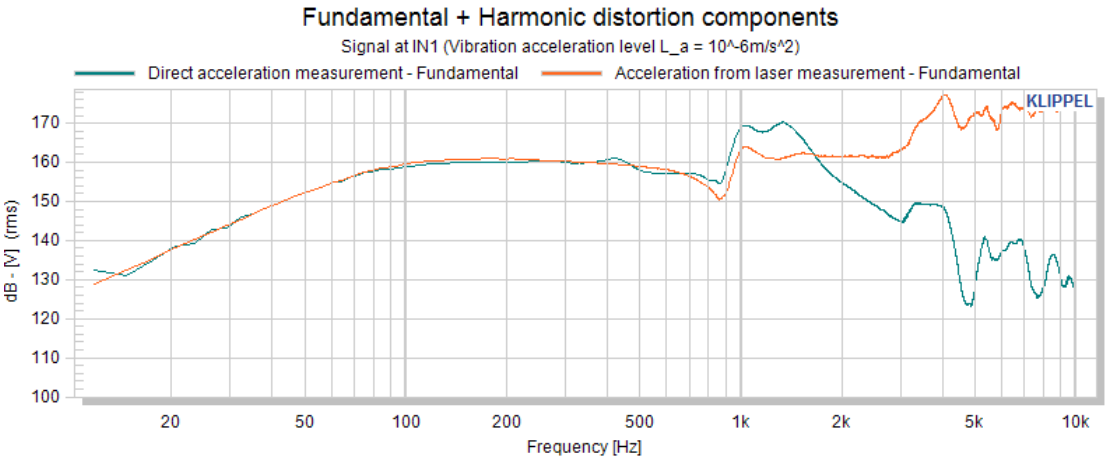
Data analysis and post processing	For the detailed analysis of the measurement all features of the *TRF* module can be used, like windowing, smoothing, etc. The Fundamental curve in window ***Fundamental + Harmonics*** should be used for further processing. There you get the absolute acceleration level in dB (with reference acceleration $a_{Ref} = 10^{-6}$ m/s^2).  **NOTE:** Since the physical context of differentiating the fundamental twice could not be covered by the reference curve, the shown y–axis label ***dB - [mm] (rms)*** is not correct. It should be ***dB - [m/s^2] (rms)*** instead. If you are interested in the absolute acceleration in [m/s^2] or in [g] then you may run the additional post-processing operation (*PPP* license needed). This calculates the acceleration values from the *TRF* measurement.  The peaks in the calculated acceleration above 3 kHz are due to the break up modes of the loudspeaker cone. This is a normal behavior of the loudspeaker which can be investigated in more detail using the KLIPPEL Scanning Vibrometer (SCN).
Harmonic distortion	Since the displacement signal has a too low SNR above resonance frequency, the measured signal is not suitable for calculating harmonic distortion (normally they are located at about 30 dB below the fundamental which means that you need even better SNR for measuring them). Thus, if you are interested in the harmonic distortion components, please do not use the displacement or acceleration but use a microphone measurement instead.

3 Comparison with acceleration sensor

Accelerometers have some disadvantages when measuring the acceleration of loudspeaker diaphragms directly. Since they act as an additional mass when mounted to the diaphragm, this will lower the overall measurement bandwidth. There will be an additional resonance frequency of the acceleration sensor which leads to a low-pass characteristic in the measured signal. This additional resonance frequency affects the acceleration sensor only - measuring the displacement of the membrane at the same time does not show this bandwidth limitation (see below chart).

For comparing both, the direct measurement technique with the calculation from the displacement measurement, this application note uses a 5 inch woofer with relatively high moving mass compared to the sensor weight.

The database that comes with this application note contains a comparison measurement using a small accelerometer (ca. 0.8 g) mounted with wax to the dust cap of the woofer. Please see the window ***Fundamental + Harmonics*** of the comparison measurement which contains the fundamental curves of the accelerometer measurement (green) and the laser sensor measurement (orange).



You can see that both curves are matching quite well up to about 600 Hz. Above this frequency the directly measured acceleration starts to rise above the calculated acceleration before it decreases with about 12 dB per octave while the calculated acceleration stays stable until the cone breaks up above 3 kHz.

This behavior of the direct acceleration measurement is due to the resonance between the membrane of the transducer and the accelerometer itself. This resonance is at about 1 kHz in this case, it may be shifted to higher frequencies by attaching the sensor to the membrane more rigidly (which is not possible in some cases). Above the resonance frequency, between sensor and DUT, the measured acceleration decreases, which means that there is a maximum frequency that can be measured with the direct measurement technique.

NOTE: The resonance frequency between acceleration sensor and DUT highly depends on how rigidly the sensor is attached to the DUT. When measuring up to very high frequencies the sensor has to be screwed or glued to the measured surface, which is of course not possible for loudspeakers. That is why it may be hard measuring loudspeakers with acceleration sensors directly.

However, since this application note uses the displacement measurement with a laser sensor that does not act as an additional mass, there is no additional resonance frequency between sensor and DUT which limits the measurement frequency range. The only limiting factor of this measurement is the decreasing displacement at higher frequencies which limits the SNR in the measured displacement signal and thus, also in the calculated acceleration.

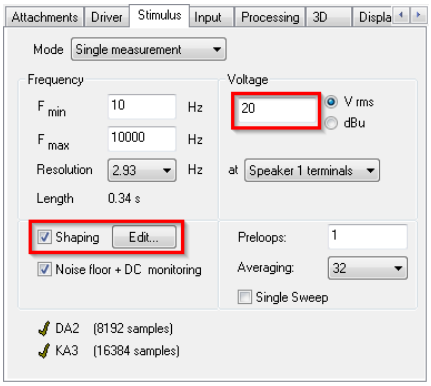
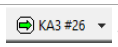
For the example measurement with the laser displacement sensor it did not make a difference whether the acceleration sensor was attached to the DUT or not. The resonance of the acceleration sensor does not have any effect on the laser measurement. The shown measurements with the laser sensor were done at a point on the membrane next to the acceleration sensor.

4 Measurement at higher frequencies

4.1 Performing measurement

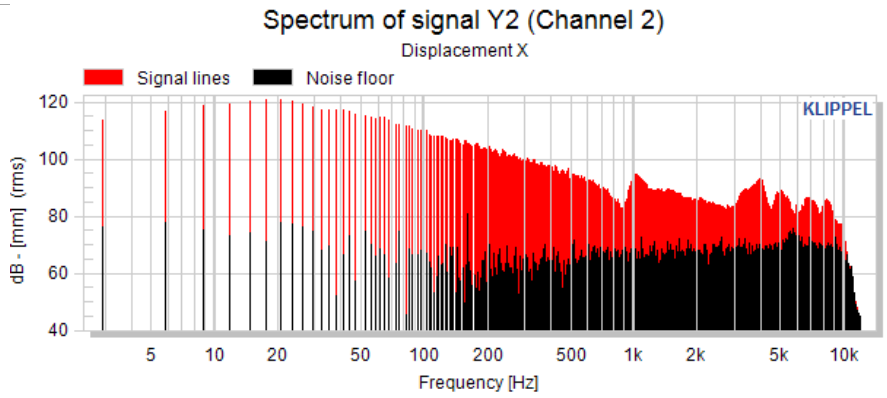
As described above, the laser displacement measurement may suffer from the 12 dB per octave decrease of the displacement above the resonance frequency.
If you are interested in seeing the displacement (and calculated acceleration) also at higher frequencies, you have to use the stimulus shaping feature of the *TRF*.

The following instructions can be used for modifying the *TRF* operation in the template.
There is an additional example measurement in the example database that comes with this application note using the stimulus shaping. This example measurement may also be used as a template.

Stimulus Settings	Open the ***Property Page*** of the *TRF* Operation and select the ***Stimulus*** Tab. Please edit the shaping curve according to your transducer. A good starting point for woofers might be the settings from the example measurement. Background information for this configuration will be discussed in section 5. Additionally you need to increase the stimulus level because you want to get high displacements at high frequencies.  **NOTE**: Most likely you have to modify the stimulus voltage or apply some other shaping which is suitable for your DUT (with respect to its resonance frequency). Please always check the time signal of the measured displacement if it is within an acceptable range. **CAUTION!** A too high voltage or a too low shaping slope can damage and destroy your loudspeaker! No warranty is given for any measured loudspeaker.
Input Settings	The Input settings stay the same as for the template without stimulus shaping.
Processing	The Processing settings stay the same as for the template without stimulus shaping.
Run the Measurement	After finishing the configuration press the green arrow to ***run***  the operation.

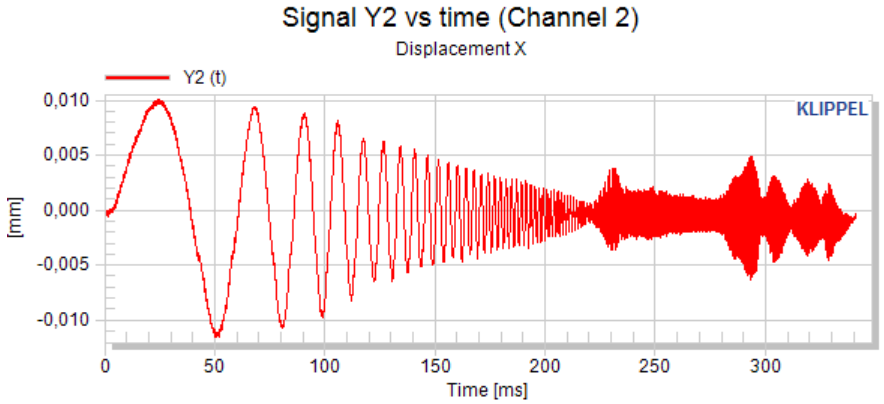
4.2 Results

Spectum Y2(f)	Open the window ***Y2 (f) Spectrum***. In case you have enabled the *Noise Floor + DC monitoring* in the stimulus settings (always recommended) you will see the black lines of the measured noise floor and the red lines of the measured displacement in this chart. When using the stimulus shaping you should get a distance between the highest black lines (noise) and the lowest red lines (signal) of at least 20 dB up to high frequencies. If this difference is lower, you may duplicate the measurement operation and perform it again with higher stimulus voltage or higher number of averages. Also changing the stimulus shaping curve may be possible for generating higher displacement at high frequencies while the displacement at low frequencies keeps the same.



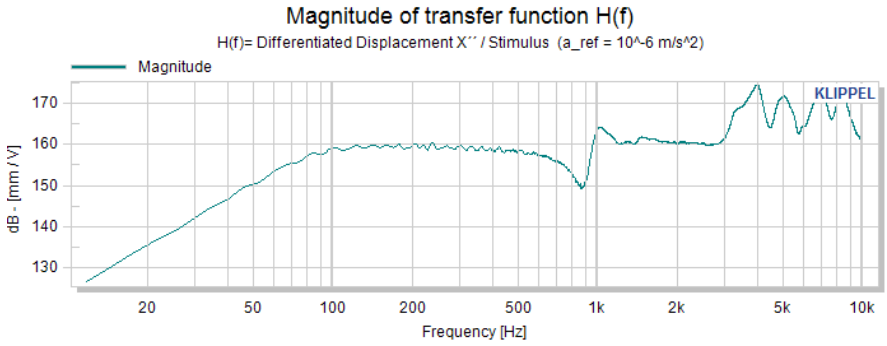
Displacement signal Y1 (t)

The ***Y1(t)*** window shows the measured time signal of the displacement measurement. This window is a good indicator to check if the speaker is within its displacement limits.
If the speaker has already high displacement at low frequencies but still not enough displacement at higher frequencies (low SNR), you should increase the stimulus shaping.



Data analysis and post processing

For detailed analysis of the measurement all features of the *TRF* module can be used, like windowing, smoothing, etc.
Since the Fundamental curve is also affected by the stimulus shaping, it cannot be used for further processing. Instead, please use the transfer function in window ***H(f) Magnitude*** because this does not contain the effect of the stimulus shaping. Please note that the magnitude of transfer function is always displayed as for a stimulus voltage of 1 V, so changing the stimulus voltage should not have an effect on this curve (except for compression and other non-linear effects).



The *PPP* template may also be used for calculating the acceleration in [m/s^2], but as already mentioned the absolute acceleration from the fundamental curve is not usable. Thus, the *PPP* template has to be modified for using the magnitude of the transfer function instead. Please refer to the *PPP* manual on how to change the curve input C1.

5 Further information

This section will provide further background information on how to set the properties of the *TRF* operation and why. Stimulus settings for getting proper SNR in the laser signal are important as well as understanding how to get from the measured displacement to acceleration.

5.1 Stimulus settings (only when using stimulus shaping)

The displacement of every loudspeaker decreases with 12 dB per octave above the resonance frequency, which means that it is very hard getting proper SNR in the laser displacement signal at higher frequencies. Thus, the stimulus shaping in the *TRF* is used to compensate for the decrease in displacement.

NOTE: Due to the fact that the displacement is constant below the resonance frequency, you should apply shaping only above this frequency. This is especially important for micro-speakers that have a relatively high resonance frequency.

The (rms) voltage of the shaped stimulus can be adapted to the currently measured loudspeaker.

The specified voltage will be reached at the highest frequency Fmax, while all lower frequencies will be attenuated according to the shaping.

For finding a proper voltage setting it is strongly recommended to start with a very low voltage and to cautiously increase the voltage until the desired signal-to-noise ratio is reached (review the spectrum of the displacement signal).

The shaping curve of the stimulus can be changed using the button next to the checkbox *Shaping* on property page *Stimulus* in the *TRF*. In the example database, which is provided with this application note, a logarithmical shaping of 20 dB per decade (equal to 6 dB per octave) is used above a frequency of 100 Hz. This is already a good starting point for a new measurement. A range from 6 dB per octave up to 12 dB per octave is practical to protect the loudspeaker from too high voltages and displacements at low frequencies.

It is always recommended having a look to the absolute displacement in the time signal of the measured displacement. This ensures not to overdrive the loudspeaker mechanically at low frequencies.

CAUTION! A too high voltage or a too low shaping slope can damage and destroy your loudspeaker! No warranty is given for any measured loudspeaker.

5.2 Calibrating the sensor

According to standard **ISO 1683** the reference value for the vibratory displacement is x_{Ref} = 1 pm and the reference value for vibratory acceleration is a_{Ref} = 1 µm/s^2.

Thus, the calibration on property page *Input* of the *TRF* for the laser displacement is set to 10^{-9} mm = 0 dB.

In case of the direct measurement with the acceleration sensor the calibration value of 0.0101 V/m/s^2 has to be taken into account. So the final calibration in the TRF setup is $1.01 \cdot 10^{-8}$ V = 0 dB (for the comparison measurement only).

5.3 Getting from displacement to acceleration

The mathematical relationship between displacement, velocity and acceleration is described by the following formula:

$$v = \frac{dx}{dt}$$

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

- where ***x*** is displacement, ***v*** is velocity and ***a*** is acceleration. Writing this with the imaginary number ***j*** and the radial frequency ***ω*** results in the following:

$$v = x \cdot j\omega$$

$$a = v \cdot j\omega = x \cdot (j\omega)^2$$

From a more practical point of view this equals a high-pass filtering of the measured displacement signal. This can easily be done by using the reference curve on property page ***Processing*** in the *TRF* setup which will be added to the measured transfer function in the *TRF*. Therefore the above formula is written as a level in dB:

$$\frac{a}{a_{\mathrm{ref}}} = \frac{(j\omega)^2 \cdot x}{a_{\mathrm{ref}}}$$

$$20log\left(\frac{a}{a_{\mathrm{ref}}}\right) = 20log\left(\frac{(j\omega)^2 \cdot x}{a_{\mathrm{ref}}}\right)$$

The second term can be separated into the measured displacement level L_x and the wanted reference level L_C:

$$20log\left(\frac{(j\omega)^2 \cdot x}{a_{\mathrm{ref}}}\right) = 20log\left(\frac{(j\omega)^2 \cdot x_{\mathrm{ref}}}{a_{\mathrm{ref}}}\right) + 20log\left(\frac{x}{x_{\mathrm{ref}}}\right) = L_{\mathrm{C}} + L_{\mathrm{x}}$$

With the radial frequency $\omega = 2\pi f$ and the vibratory displacement and acceleration from section 5.2 you end up with:

$$L_{\mathrm{C}} = 20log\left(\frac{j^2 \cdot 4\pi^2 \cdot f^2 \cdot 10^{-12}\mathrm{m}}{10^{-6}\frac{\mathrm{m}}{\mathrm{s}^2}}\right)$$

The reference curve in this example is defined from 1 Hz to 100 kHz. According to the above formula the levels for these two frequencies are (with $j^2 = -1$):

$$L_{\mathrm{C,1Hz}} \approx -88\ \mathrm{dB}$$
$$L_{\mathrm{C,100kHz}} \approx 112\ \mathrm{dB}$$

Since the measured transfer function in the *TRF* is divided by the reference curve (which means subtracting the dB values) the calculated levels as well as the phase shift have to be negated before putting them into the property page of the *TRF*:

Curve = [
1 88 180
100000 -112 180];
Format: frequency [Hz] amplitude [dB] phase [degree]

The frequency range of this reference curve should be wide enough for almost all possible applications. Of course the reference curve can also be adapted to any other frequency range. Simply use the above formula to calculate the required levels accordingly.

5.4 Calculating velocity

According to the above section you may also calculate the velocity from the measured displacement. Therefore the formula for calculating the reference curve would be:

$$L_{C,v} = 20log\left(\frac{j \cdot 2\pi \cdot f \cdot 10^{-9}\frac{m}{s}}{10^{-6}\frac{m}{s^2}}\right)$$

The ***j*** in this formula equals a phase shift of -90° in the phase of the reference curve. Thus, the reference curve for a frequency range from 1 Hz to 100 kHz would be (again negating the levels and phase shift):

Curve = [
1 44 90
100000 -56 90];
Format: frequency [Hz] amplitude [dB] phase [degree]

The calibration of the displacement sensor in the *TRF* property page "Input" does not need to be changed.

6 References

6.1 Related modules	[1] S7 - TRF –Transfer Function (TRF) [2] A2 - Laser Displacement Sensors
6.2 Manuals	[3] Manual - TRF Transfer Function (included in dB-Lab setup) [4] Manual - Hardware
6.3 Standards	[5] International Standard ISO 1683 (second edition 2008-08-15)

Find explanations for symbols at:
http://www.klippel.de/know-how/literature.html
Last updated: October 15, 2018