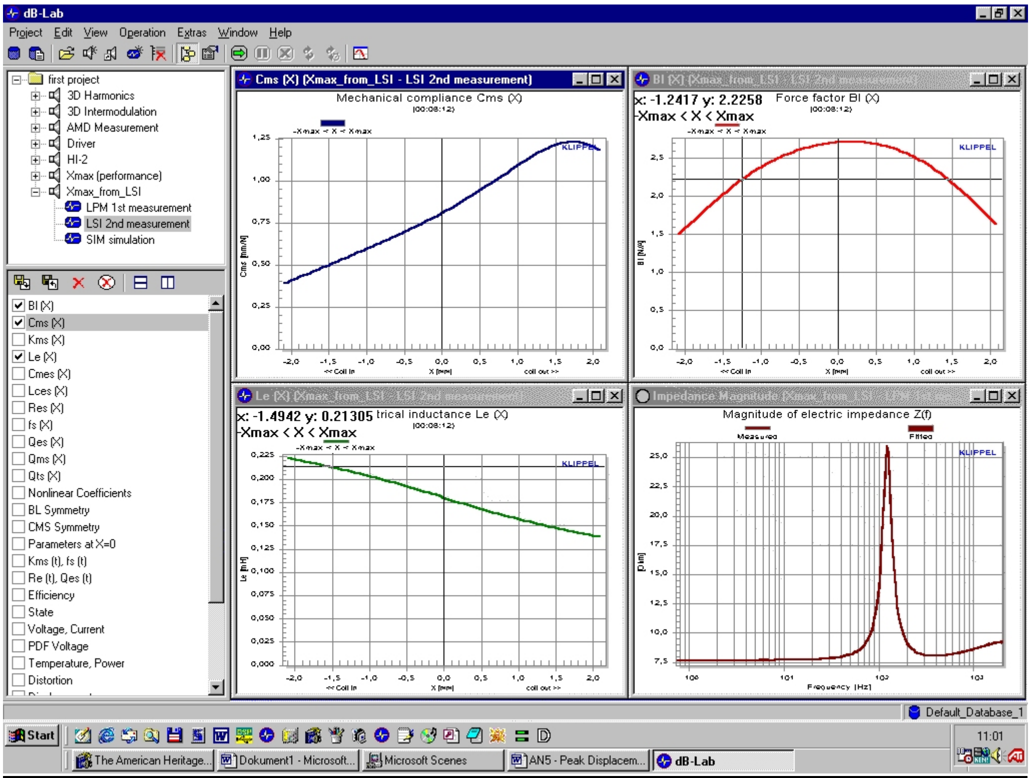
Displacement Limits due to Driver Nonlinearities **AN 5**

Application Note to the KLIPPEL R&D SYSTEM

The physical causes limiting the voice coil peak excursion Xmax are represented by separate displacement limits X_{Bl}, X_C, X_L and X_D corresponding to the dominant driver nonlinearities in the motor, suspension and radiation. These limits are derived from the large signal parameters of the driver measured by the Linear Parameter Measurement (LPM) and Large Signal Identification (LSI) using admissible thresholds of parameter variation defined by the user. The relationship between the separate excursion limits and the peak displacement Xmax determined by the performance-based method is discussed.



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Limits of Voice Coil Displacement

Physical Causes	The maximal peak displacement X_{max} is limited by at least three factors 1. Excessive decrease of mechanical compliance of the mechanical suspension (mainly caused by the natural limiting of the spider) 2. Voice coil excursion capability (mainly limited by hitting the back plate) 3. Excessive, subjectively unpleasant, signal distortion in the sound pressure output depending on speaker nonlinearities, intended application, nature of excitation signal and audible acuity of the listener These limiting factors may be represented by separate displacement limits • X_C represents mechanical loading imposed to suspension and tolerable distortion due to $C_{ms}(x)$ nonlinearity, • X_{clip} represents free moving range without clipping, • X_{Bl} represents tolerable distortion due to $Bl(x)$-nonlinearity, • X_L represents tolerable distortion due to $L_e(x)$ nonlinearity, • X_D represents tolerable distortion due to Doppler nonlinearity.
X_C	The displacement limit X_C considers the critical mechanical strain of suspension and audible distortion generated by nonlinear stiffness characteristic $K_{ms}(x)$ or from its counterpart, the compliance characteristic $C_{ms}(x)$. Defining an admissible compliance ratio $$C_{\min}(X_C) = \min_{-X_C<x<X_C}\left(\frac{C_{MS}(x)}{C_{MS}(0)}\right) * 100\,\% \qquad (1)$$ which is the ratio of the minimal value of the compliance within the working range $\pm X_C$ and the value at the rest position $x=0$. X_C is implicit in the equation and can be found in the nonlinear $C_{ms}(x)$-characteristic by using a pre-defined threshold C_{min}. A symmetrical compliance characteristic will produce about 10 % total harmonic distortion at a threshold C_{min}= 75 %.
X_{clip}	The maximal displacement due to mechanical clipping may be derived from the geometry of the moving coil assembly, and may be verified by practical experiments. In a well-designed loudspeaker, X_{clip} should always be higher than X_C to avoid a mechanical damage of the voice coil former.
X_{Bl}	The maximal displacement X_{Bl} limited by excessive motor distortion may be obtained from the nonlinear force factor characteristic Bl(x). We define the minimal force factor ratio $$Bl_{\min}(X_{Bl}) = \min_{-X_{Bl}<x<X_{Bl}}\left(\frac{Bl(x)}{Bl(0)}\right)*100\% \qquad (2)$$ which is the ratio of the minimal force factor $Bl(x)$ in the working range $\pm X_{Bl}$ referred to the *Bl*-value at the rest position $x=0$. X_{Bl} is implicit in the equation and can be found in the nonlinear $Bl(x)$-characteristic after defining the threshold Bl_{min}. The threshold Bl_{min}= 82% will produce about 10 % intermodulation distortion.

X_L	The variation of the impedance versus displacement x is directly related with the magnitude of the intermodulation distortion generated in the current and in the radiated sound pressure output. Thus, the displacement limit X_L is defined implicitly by $$Z_{\max}(X_L) = \max_{-X_L<x<X_L} \frac{\left|Z_e(x,f_2) - Z_e(0,f_2)\right|}{\left|Z_e(0,f_2)\right|} * 100\ \%$$ which is the ratio of the maximal variation of the electrical impedance at frequency f_2 within the working range $-X_L < x < X_L$ and the impedance at the rest position x=0. To keep the parameter-based method consistent with the performance-based method, the frequency $f_2 = 8.5\ f_s$ is coupled to the resonance frequency f_s. Approximating the impedance by $$Z_e(x,f_2) \approx R_e + L_e(x)s_2 + \frac{R_2(x)L_2(x)s_2}{R_2(x) + L_2(x)s_2} \quad (3)$$ where $s_2=2\pi f_2 j$ and using the power series expansion of the nonlinear characteristics $$\frac{L_e(x)}{L_e(0)} = \frac{L_2(x)}{L_2(0)} = \frac{R_e(x)}{R_e(0)} = 1 + \frac{l_1}{L_e(0)}x$$ with the linear coefficient l_1 gives the displacement limit X_L explicitly $$X_L = \frac{L_e(0)}{\left|l_1\right|} \frac{\left|Z_e(0,f_2)\right|}{\left|Z_e(0,f_2) - R_e\right|} \frac{Z_{\max}}{100\%}. \quad (4)$$ The threshold Z_{max}= 10 % will produce about 10 % intermodulation distortion.
X_D	The displacement limit X_D considering the audibility of the Doppler effect can be calculated analytically giving accessible peak displacement due to Doppler $$X_D = \frac{90.5d}{f_s} \quad (5)$$ where X_D is in mm, resonance frequency f_s is in Hz and the modulation distortion *d* in percent at f_2=8.5 f_s. The threshold of *d*= 10 % keeps the definition of X_D consistent with the performance based method. Only in drivers designed for extreme displacement the Doppler will limit the peak displacement X_{max}.
Practical Usage	1. Define the four thresholds C_{min},, Bl_{min}, Z_{max} and d according to the accessible mechanical load and the audibility of the distortion (or used the recommended values). 2. Measure the nonlinear characteristics compliance $C_{ms}(x)$, force factor *Bl(x)*, and inductance $L_e(x)$ versus displacement *x* and the voice coil resistance R_e. 3. Determine the peak displacement X_c, X_b, X_L and X_D by using the driver parameters meters. 4. Determine the maximal displacement X_{clip} due to moving capability (mechanical clipping). 5. Specify the separate limit values for voice coil displacement and the used
Relationship to Xmax	The AES 1984-2 suggests a performance-based method for assessing the maximal peak displacement Xmax based on distortion measurement. The original method is based on assessing the total harmonic distortion only and fails for drivers having significant Bl(x) nonlinearity. An amendment suggests a two-tone signal for the measurement of the harmonics and intermodulation distortion. Although there are fundamental differences between the performance-based and the parameter-based approach it is possible to keep both method

comparable by choosing corresponding distortion values d_t, d_2 and d_3 and thresholds Bl_{min}, C_{min}, Z_{max}, d.

To avoid any confusion it is recommended to use the expression *Voice Coil Peak Displacement* and the symbol Xmax for the results of the performance-based approach only. The minimum of Displacement limits represents the physical cause for limiting Xmax.

Using the Klippel R&D System

Requirements

- Distortion Analyzer + PC
- dB-Lab
- Linear Parameter Measurement (LPM) software module
- Large Signal Identification (LSI Pro) software module
  (Manual calculation is possible with LSI Standard)
- Laser sensor head + controller

Setup

Mount the driver in the laser stand and connect the terminals with SPEAKER 1. Switch the power amplifier between OUT1 and connector AMPLIFIER. Adjust the laser head to a white dot on the diaphragm.

Preparation

1. Create a new object DRIVER based on the template *LSI Displacement Limits AN 5* provided in the dB-Lab object templates.

1st Measurement

If you know the force factor Bl(x=0) at the rest position of the driver you may skip the first measurement. Alternatively you may use the *LPM 1st measurement* with the setup parameters provided.

1. Select and start the measurement LPM 1st Measurement
   Make sure the signal level is appropriate for an LPM measurement. Adjust level, and repeat if necessary. (see LPM Specification).
2. Open the property page IMPORT/EXPORT and export all parameter to the clipboard.

2nd Measurement

1. Select the "LSI 2nd Measurement"
2. Open property page IM/EXPORT. Import the linear parameters from the LPM 1st measurement, click **import from clipboard**. Alternatively, specify Bl(x=0), M_{ms} and $Re(\Delta T_V=0)$ manually.
3. Start the measurement.
   Listen for excessive distortion and assign $X_{clip}=X_{peak}$ in case of a mechanical defect. Click "Finish" after completion of the nonlinear mode.
4. Open the Window "Nonlinear Parameters".
   The window specifies the displacement according to the recommended specification.

By default, the LSI uses the recommended thresholds for calculation of the displacement limits. For more information, see below, "Setup Parameters" – "2nd Measurement".

Setup Parameters for the LPM and LSI Module

Template

Create a new Object, using the object template **LSI Displacement Limits AN 5** in dB-Lab. Then the two measurements are already customized for the assessment of X_{max}. If this database is not available you may generate an LPM and an LSI measurement, using the following setups.

1st Measurement

Create an empty object named Displacement Limits. Assign an operation LPM Linear parameter measurement to this object.

1. On the property page *Stimulus*, set resolution of 1/16th octave of the multi-tone signal starting from 20 Hz up to maximal frequency 2000 Hz. Set number of averaging to 8.
2. Set stimulus to 0.1 V (RMS) at the speaker terminals. You might need to modify this according to your speaker.
3. On property page Input select SPEAKER 1 and enable the Laser as external sensor.

2nd Measurement

1. Assign an operation LSI Large Signal Parameters to the object Displacement Limits.
2. On the property page *Protection*, and confirm that the settings are appropriate for your driver. If you change any of the protection limits, Please note that the protection limits should be lower than the threshold limits (see below).

3. On the property page *Conditions*, select *Finish task after: Nonlinear Mode*.

Optionally, you can change the thresholds at which the displacement limits are specified. To do that:

1. Select the property page *Series*. In the *Displacement Limits* group, click on *Edit*
2. Edit the thresholds according to your needs.

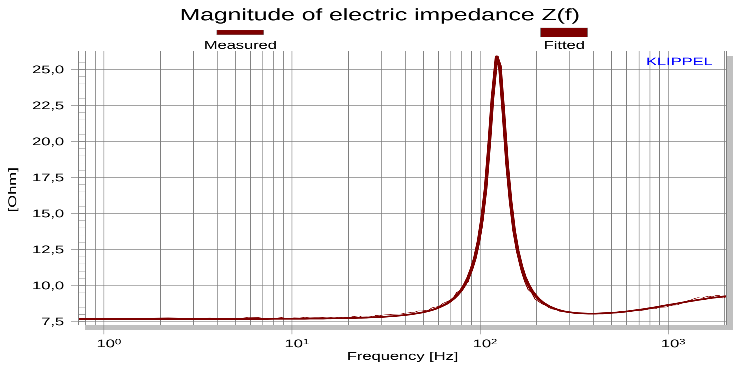
The protection limits for Bl_{lim} and C_{lim} should be about 20% lower than the thresholds. This ensures accurate parameters in the displacement limit range. The Threshold editor dialog displays a warning message when the selected thresholds conflict with the current protection limits. You might need to adjust the protection settings accordingly.

The thresholds can be modified after the measurement ran. However, when you need to change the protection parameters, you also need to run the measurement again.

Example

This example explains how the displacement limits can be calculated manually. The current version of the LSI Pro does the calculations automatically.

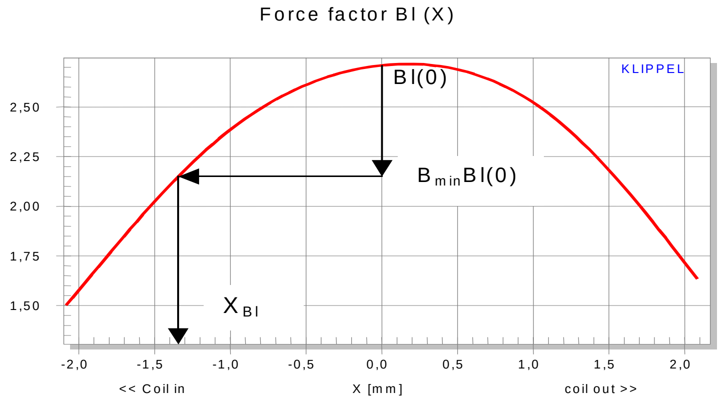
Linear Parameters



The LPM 1st measurement provides the linear parameters of the driver. The force factor Bl(0), the moving mass M_{ms} and the voice coil resistance R_e are exported to the 2nd measurement. For manual calculation, the resonance frequency f_s is required for the assessment of X_L and X_D due to inductance nonlinearity and Doppler effect.

X_B

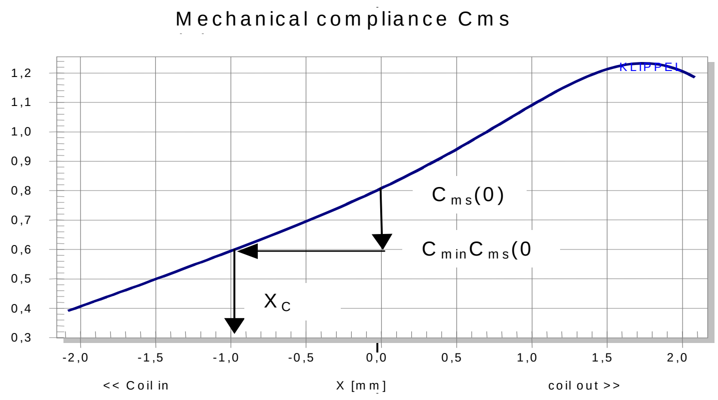
The LSI 2nd measurement provides the nonlinear parameters of the driver. Open the window Bl(x) and read the peak displacement X_B where the Bl(x) is reduced to the value Bl_{min} times the value Bl(0) at the rest position.



For the particular driver in the example the peak displacement X_B= 1.38 mm due to force factor using a limit Bl_{min}=82 %.

X_C

Open the window $C_{ms}(x)$ and read the peak displacement X_C where the $C_{ms}(x)$ is reduced to the value C_{min} times the value $C_{ms}(0)$ at the rest position.



For the example driver the peak displacement X_C is 0.98 mm using C_{min}= 75 %.

X_L

Open the window *Nonlinear Parameters* and read the linear coefficient L_1 = 0.05 mH/mm. Open the window *Parameters at X=0* and read the parameters R_e= 7.5 Ohm, $L_e(0)$= 0.5 mH, $R_2(0)$= 1 Ohm, $L_2(0)$=0.01 mH and f_s= 113 Hz. Use Eq. (3) to calculate $|Z_e(0, f_2)|$= 8.07 Ohm and $|Z_e(0, f_2)-R_e|$=3 Ohm. Use Eq. (4) to calculate X_L =2.7 mm.

X_D

For a resonance frequency f_s= 113 Hz and a limit of d= 10 % the Doppler effect will limit the peak displacement to X_D= 8 mm.

X_{clip}

During the LSI identification no excessive distortion are generated that are caused by hard limiting of the voice coil displacement. Thus X_{Clip} > 2mm.

Specification

The maximal peak displacement is limited by stiffness nonlinearity X_C= 0.98 mm

whereas

X_{Bl}= 1.38 mm @ B_{min}=82 %
X_C= 0.98 mm @ C_{min}= 75 %
X_L= 2.7 mm @ Z_{max}= 10 %
X_{clip} > 2 mm
X_D = 8 mm @ d = 10 %

More Information

Papers

W. Klippel, "Assessment of Voice Coil Peak Displacement X_{max}, paper in presented at the 112th Convention of the Audio Engineering Society, 2002 May 10 – 13, Munich, Germany. Updated version on Updated version on http://www.klippel.de/know-how/literature/papers.html

Application Notes

"Measurement of Peak Displacement Xmax (performance-based method)", AN 4 of the KLIPPEL R&D SYSTEM

Related Specification

“LPM”,S1
“DIS”, S4

Software

User Manual for KLIPPEL R&D SYSTEM.

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