Assessment of Voice Coil Peak Displacement X_{max}

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ABSTRACT

The voice coil peak displacement X_{max} is an important driver parameter for assessing the maximal acoustic output at low frequencies. The method defined in standard AES 2-1984 is based on a harmonic distortion measurement, which does not give a definite and meaningful value of X_{max}. After a critical review of this performance-based technique, an amendment of this method is suggested by measuring both harmonic and modulation distortion in the near field sound pressure using a two tone excitation signal. Alternatively, a parameter-based method is developed giving more detailed information about the cause of the distortion, limiting and defects. The relationship between performance-based and parameter-based methods is discussed, and both techniques are tested with real drivers.

1 Introduction

Loudspeakers that have similar linear parameters may behave quite differently at higher amplitudes. In the large signal domain, the physical limits require a compromise between maximal amplitude, efficiency, signal distortion, cost, weight, size and other factors.
Thus, assessing the large signal performance by a number of meaningful parameters becomes more and more important. There are a few "traditional" parameters describing admissible load and the maximal output of the driver. One of them is the maximal (linear) peak displacement X_{max} showing the maximum of displaced air volume which limits the maximal sound pressure output at low frequencies as shown in Fig. 1.

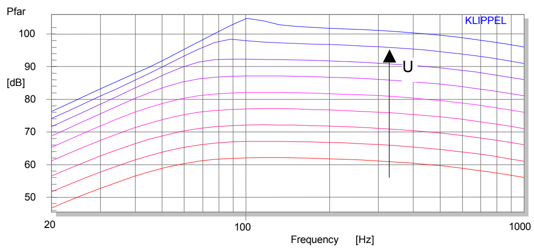

Fig. 1: Fundamental of radiated sound pressure frequency response in 1 m distance measured at various input voltages U increased in 5 dB steps.

The parameter peak displacement X_{max} is listed on every serious specification sheet which is the interface between driver and loudspeaker system design. However, manufacturers use different ways to assess X_{max} and stated values are not comparable:
1) Historically, the first approach is a geometric-based method where X_{max} has been derived from geometrical data such as voice coil overhang and principal moving capabilities of the suspension. This approach neglects the voice coil offset, magnetic field asymmetries, suspension problems and other driver defects.
2) The performance-based method considers these things and measures the overall behavior of the final driver. For years harmonic distortion measurements compared with a threshold of 10 % distortion have been used as a criteria for defining X_{max} [1, 2, 3]. Almost 20 years ago a method based on this approach was defined in the AES-standard AES-2 1984. Unfortunately, some points of this method do not work satisfactorily and this method was not used as a common reference either in professional or in other audio fields. Thus, the current revision of this AES-2 standard requires an amendment of the X_{max} definition.
3) D. Clark [7] suggested the parameter-based method using the nonlinear force factor and compliance characteristic for assessing X_{max}.
4) Finally, there are undefined methods used by manufactures resulting in impressive values of X_{max} without clear relationship to physics involved.
Since the loudspeaker system design requires reliable data to select the optimal driver, there is a permanent interest in quantifying this parameter more objectively.
A task group SC 04-03-C of the AES standard committee was founded to "*improve the definition, measurement and interpretation of the large-signal parameters by applying results of thermal and nonlinear transducer modeling"*. This paper summarizes the main results of this work and presents suggestions for defining the peak displacement X_{max} more clearly.

2 Critical Review of AES 2-1984

2.1 Definition of X_{max}

The current standard defines

... the voice-coil peak displacement at which the "linearity" of the motor deviates by 10%. Linearity may be measured by percent distortion of the input current or by percent deviation of displacement versus input current. Manufacturer shall state method used. The measurement shall be made in free air at f_S."

2.2 Ambiguities

In the current definition the linearity of the motor determines the peak displacement X_{max}. The linearity is assessed by measuring the performance of the speaker for a special stimulus. Apparently, a single tone at the resonance frequency f_s with variable voltage U is used as excitation signal. The nonlinearities in the driver will produce a nonlinear relationship between the input and output amplitude. At high amplitudes, we expect less output than predicted by linear modeling (amplitude compression). A spectral analysis of the output signal reveals further symptoms of nonlinear behavior. In addition to the fundamental component at the excitation frequency f_s, the nonlinearity generates additional spectral components at multiple frequencies (harmonics). In displacement we may find a DC part generated dynamically by asymmetrical nonlinearities. The definition uses "percent distortion" and "percent deviation" as a measure of linearity but it is not clear to which symptom this is applied (harmonics or amplitude ratio between input and output) and how it is defined (total or separate harmonics).
The measurement of the performance will not directly show the linearity of the electrodynamic "motor" as a separate part, but more the linearity of the total driver considering effects of other electrical, mechanical and acoustical parts such as the suspension.
The ambiguities require some "active" interpretation of the definition. Some users interpreted the percent distortion and percent deviation as total harmonic distortion d_t according to the IEC 60268.

2.3 Assumptions

More critical than the ambiguities of the definition are the assumptions made:

- The measurement of harmonic distortion in current or displacement produces comparable values of X_{max}.
- There is a simple relationship between amplitude of the distortion and peak displacement.
- The distortion increases monotonically with amplitude of input signal, and 10% distortion corresponds to only one, unique value of X_{max}.
- The measurement of harmonic distortion at the resonance f_s reveals effects of motor nonlinearity adequately.

2.4 Fictitious Driver

We check the validity of the assumptions by applying the current X_{max} definition to a fictitious driver with the following properties:

Parameter	Value	Unit
R_e	3.5	Ohm
$L_e(x)$=const.	1	mH
$C_{ms}(x)$=const.	0.7	mm/N
Q_{ms}	7	
f_s	47	Hz

Table I: Small Signal Parameters

The force factor (*Bl*-product) has a nonlinear characteristic as shown in Fig. 2.

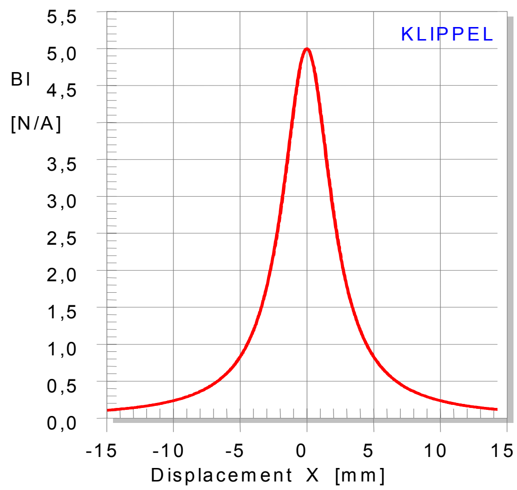

Fig. 2: Bl(x)-product versus voice coil displacement of the fictitious driver used in the simulation.

The force factor *Bl(x)* is not a constant parameter but a function of voice coil displacement. The *Bl(x)* has a symmetrical bell-shaped form approaching zero for high displacement. A voice coil with a height of 5 mm and a stray field outside the gap may cause such a characteristic. The early strong decay of the *Bl*-curve is typical for a short voice coil overhang. Since the *Bl(x)*-curve is perfectly symmetrical to $x=0$ the driver produces only third and other odd-order distortion.
All other nonlinearities inherent in real drivers are neglected in the fictitious driver to keep our test case as simple as possible. Thus we assume a linear suspension having a constant compliance $C_{ms}(x)$=const. and a voice coil inductance $L_e(x)$ that is independent on displacement. For the validity check those simplifications are admissible because our goal is to find at least one case where the assumptions of the current definition fails.
According to the measurement conditions defined in AES2-1984, we operate the driver in free air.

2.5 Simulation of Large Signal Behavior

The fictitious driver can be precisely modeled by the nonlinear differential equation. Applying numerical integration [4] all the state variables (current, displacement, etc.) and the acoustical output signal may be predicted for any input signal and may be subjected to a FFT analysis. Exciting the driver with a single tone at f_1=f_s with varied terminal voltage U_1 Fig. 3 shows the total harmonic distortion

$$d_t = \frac{\sqrt{P(2f_1)^2 + P(3f_1)^2 + ... + P(Kf_1)^2}}{\sqrt{P(f_1)^2 + P(2f_1)^2 + P(3f_1)^2 + ... + P(Kf_1)^2}} * 100\ \%$$

of the current, sound pressure and displacement versus peak displacement $X_{rms}(f_1)$.

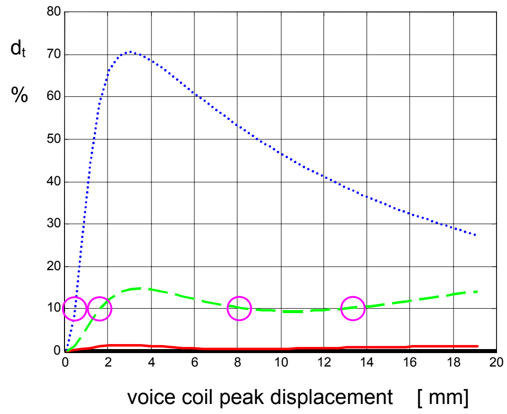

Fig. 3: Total harmonic distortion in current (dotted line), sound pressure (dashed line) and displacement (solid line) for a single excitation tone at f_s versus voice coil peak displacement X

2.6 Applying X_{max} definition

To find the peak displacement X_{max} according to the AES2-1984 we have to search for peak displacement giving d_t=10 %. Using the total distortion in the input current we get a value X_{max} about 0.6 mm. That is a very small value compared to the voice coil height of about 5 mm. No manufacturer would agree to specify the working range of his loudspeaker to such a small signal domain. In this range of -0.6 mm < x < 0.6 mm the *Bl(x)* varies only by 5 % and the distortion in the radiated sound pressure is merely 2 %. Most likely the manufacturer would consider the alternative method. The total harmonic distortion in displacement remains very small and does not reach 10 % even if the coil is entirely outside the gap. Only common sense (but not the current definition) prevents a manufacturer from setting the peak displacement X_{max} to 19 mm and more.

2.7 X_{max} from sound pressure distortion

Some users modified the current X_{max} definition and applied the threshold of 10 % to the total harmonic distortion in the radiated sound pressure. Usually this provides more reasonable estimates of X_{max}. However, we might get multiple values of X giving the same value of distortion. For example the fictitious driver provides three different values 1.5 mm, 8 mm and 13.5 mm as candidates of X_{max}. What is the right value to state?

2.8 What is wrong with the definition?

Apparently the assumptions made in the current X_{max}-definition are not valid.
First, the harmonic distortion in current and displacement at f_s are not in the same order of magnitude. The reason is quite simple. The amplitude of the fundamental component of the voice coil current is minimal at the resonance frequency f_S where the electrical impedance is maximal.
However, the generated harmonic components see much lower impedance at higher frequencies and therefore get "boosted" to higher amplitude value. This effect of fundamental's "suppression" is typical only for the voice coil current and is inherent neither to displacement nor to sound pressure.
There is also no simple relationship between harmonic distortion and peak displacement. Instead of a monotonically increase we observe that the distortion stagnates at a relatively small value giving multiple values for X_{max}. Fig. 4 shows the fundamental of the displacement versus terminal input voltage.

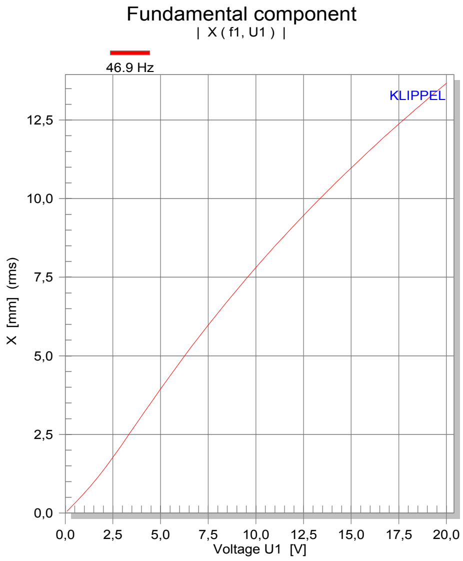

Fig. 4: Amplitude of the displacement for a tone at f_s versus input voltage U_1

For a 5-mm peak displacement, the instantaneous level of force factor *Bl(x)* reduces to 20 % and at 12 mm the force factor almost vanishes. Surprisingly, the motor works properly and we still get almost a linear relationship between displacement and voltage. There are two reasons for that:

- The electrical damping caused by $Bl(x)^2/R_e$ decreases and the mechanical Q_{ms} dominates the total damping Q_{ts}. The rising value of Q_{ts} compensates for the reduced excitation force $F = Bl(x)i$.
- The 90-degree phase shift between the current i and displacement x at the resonance frequency still provides good excitation conditions as shown in Fig. 5. When the current is maximal the coil still remains in the gap and the instantaneous value of *Bl(x)* is also maximal thus producing a high driving force $F = Bl(x)i$ and a good excitation of the system.

When the coil is outside the gap, we have a relatively high current determined by the DC resistance R_e, but when the coil moves through the gap some back EMF is generated, which produces the small dip in the current waveform.

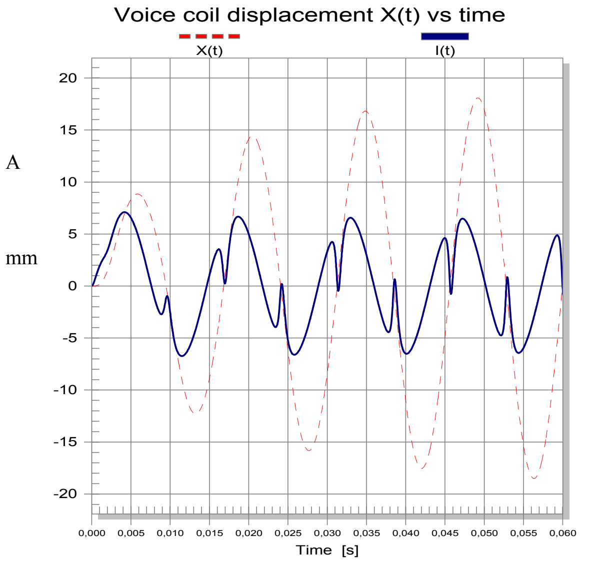

Fig. 5: Voice coil current i and displacement x versus time for an excitation tone at resonance frequency f_s.

Above and below the resonance frequency, variation of *Bl(x)* have a significant effect on the output. Fig. 6 shows the amplitude of voice coil displacement X_{rms} as a function of frequency at varied input voltage U_1.

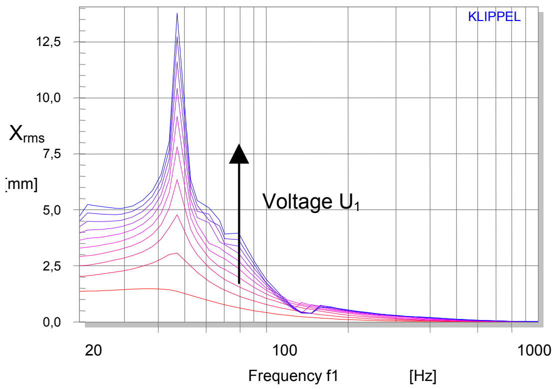

Fig. 6: Amplitude of Voice Coil Displacement of the fictitious driver excited by a single tone f_1 for varied voltage (2 V steps)

Although we are increasing the voltage U_1 from 2 V up to 20 V in 2 V steps, we observe a slower increase of the displacement (amplitude compression) at frequencies below and above the resonance f_S. This effect is mainly caused by the phase relationship between current i and displacement x where a current maximum coincides with a reduced *Bl(x)* giving less excitation force $F=Bl(x)i$ to the fundamental component. Excitation tones one octave above resonance may cause an unstable behavior at high voltages U_1 which is typical for the electrodynamical motor. Even if the rest position of the coil is well centered in a symmetrical *Bl(x)* curve, the coil has the tendency to slide down on both slopes of *Bl*. In the frequency range where we find significant amplitude compression some of the provided energy is transformed into higher-order harmonics. Fig. 7 shows the total harmonic distortion d_t in the radiated sound pressure versus frequency f of the excitation tone for varied amplitude U_1.

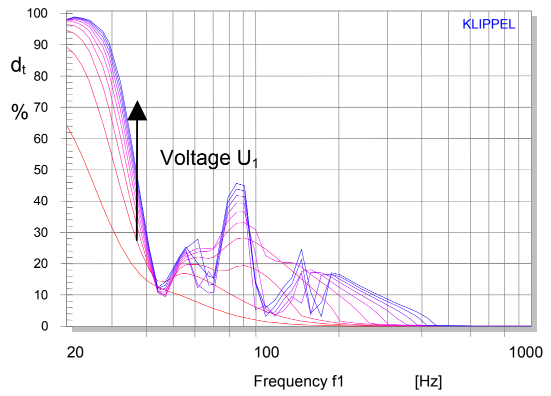

Fig. 7: Total harmonic distortion in the radiated sound pressure of the fictitious driver excited by a single tone f_1 for varied voltage (2V steps)

The harmonic distortion is maximal at excitation frequencies below resonance. This is not only caused by the low excitation force $F=Bl(x)i$ due to the coincidence of current maximum and $Bl(x)$ minimum but more by the lowpass characteristic in the radiation of the frequency components below f_s.
At the resonance frequency there is a pronounced minimum and the total harmonic distortion measurement has a blind spot for detecting $Bl(x)$-nonlinearity. However, there is a second maximum approximately one octave above resonance where we still have high amplitudes of current and displacement but the phase relationship between them gives less optimal excitation. At higher frequencies $f > 10f_s$ where the amplitude of displacement gets small the harmonic distortion becomes negligible. This is typical for any driver with $Bl(x)$ nonlinearity.

3 A new Performance-based method

Although the current method for assessing X_{max} based on the harmonics distortion measurement fails, the general ideas of this approach are still interesting:

- Derive X_{max} from driver's performance
- Dispense with a physical driver model
- Use standard measurement equipment
- Keep procedure simple and fast.

3.1 Critical Distortion Measurements

A single tone is a very popular stimulus in distortion measurements because it can be easily generated, and the measured harmonic distortion can be presented in relation to the excitation frequency. These results represent quite well the total distortion produced by more complex audio signals as long as the transfer system comprises only static non-linearities imbedded in linear systems with an almost flat amplitude response. For example the limiting of a power amplifier can be modeled by a memory-less system. Here a measurement with a single tone is adequate and the harmonic distortion has some meaning for a music signal of the same amplitude.

The dominant non-linearities in electrodynamic transducer are the parameters varying with voice coil displacement. The displacement x is a low-pass filtered signal; also, the other state variables such as current i, velocity v have a different spectral characteristic. In the nonlinear terms in the differential equation such as the excitation force $F=Bl(x)i$, the time signals are multiplied with each other and produce distortion components at all combinations of the input frequencies. The instantaneous spectrum of current, displacement and velocity determines the spectral characteristics of the distortion in the output signal. The results of a harmonic distortion measurements based on a single tone stimulus are not sufficient to predict the distortion of the transducer generated by a more complex excitation signal.

3.2 Two-tone excitation signal

Measurements of intermodulation components are therefore required to get more meaningful results. There are many ways for performing such measurements [5]. Usually, a multi-tone stimulus is used comprising two or more components. An extensive number of excitation tones might represent an audio signal quite well, but also produce a lot of data, which have to be interpreted [6]. The current IEC standard 60268, however, provides a more practical approach. A two-tone signal will provide us with the most important information if the frequencies f_1 and f_2 of the first and second excitation tones are selected carefully. Since the dominant nonlinearities of most common transducers are related with displacement, we have to use the first tone f_1 for generating some voice coil displacement. Since this tone should be close to the resonance frequency, we may call f_1 the bass tone. The second tone f_2 may represent any higher frequency component in the pass band of transducer. Hence we will call it voice tone. Fig. 8 shows the sound pressure spectrum of the fictitious driver excited with a two-tone stimulus represented as bold lines.

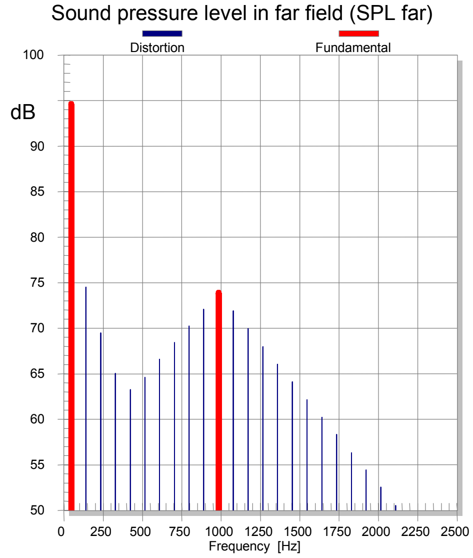

Fig. 8: Spectrum of radiated sound pressure signal of the fictitious driver excited by two tones $f_1=f_s$ and f_2=980 Hz at $U_1=U_2$=20 V_{rms}.

The thin lines in the SPL spectrum in Fig. 8 are the harmonic components at multiple frequencies of f_1 and the difference and summed-tone intermodulation at f_2-k*f_1 and f_2+k*f_1, respectively, centered around the voice tone f_2. Usually all higher-order components decrease rapidly with rising order k. Thus, the IEC standard 60268 considers only the low-order components summarized as second-order modulation distortion

$$d_2 = \frac{P(f_2 - f_1) + P(f_2 + f_1)}{P(f_2)} * 100\ \%$$

and third-order intermodulation distortion

$$d_3 = \frac{P(f_2 - 2f_1) + P(f_2 + 2f_1)}{P(f_2)} * 100\ \%$$

referred to the amplitude of the voice tone f_2.
Although the amplitudes of both excitation tones are equal, the SPL fundamental f_2 in Fig. 8 is more than 20 dB lower than the fundamental at $f_1=f_s$. The amplitude compression of the voice tone f_2 is shown more clearly in the Fig. 9 where the SPL of both fundamentals is displayed versus terminal voltage $U_1=U_2$.

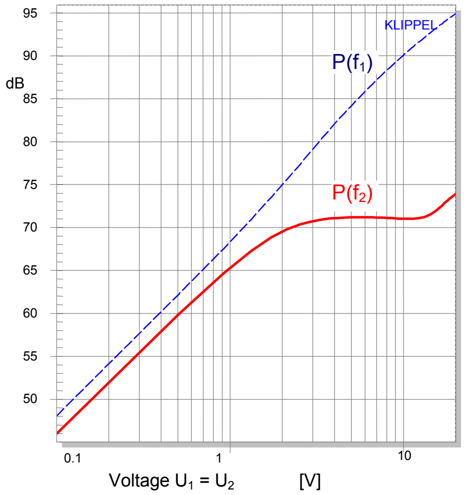

Fig. 9: Amplitude of fundamental sound pressure component for a two-tone excitation signal at $f_1=f_s$ and f_2=780 Hz versus input voltage $U_1=U_2$.

For terminal input voltages below 2 V where the peak displacement is below 1.5 mm we have a linear relationship between input and output amplitude. At higher voltages the SPL of the voice tone stagnates because the coil will leave the gap for most of the time and the effective excitation of f_2 will not rise. Please note that if we measure the voice tone f_2 without the bass tone f_1, we will have almost no amplitude compression.

Fig. 10 shows the third-order modulation distortion according to the IEC standard versus frequency f_2 while the bass tone is fixed to the resonance frequency $f_1=f_s$. The voltage $U_1=U_2$ is increased by 2 V steps.

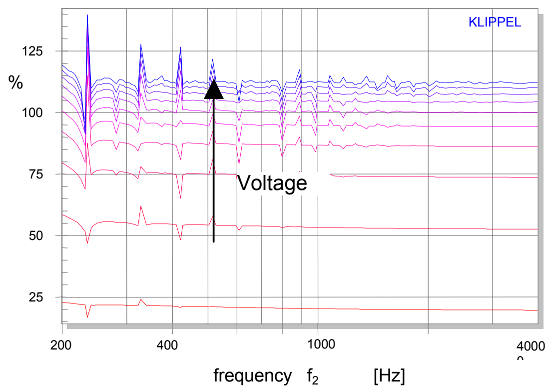

Fig. 10: Third-order intermodulation distortion in the radiated sound pressure response for two-tone excitation comprising a variable tone f_2 and a fixed tone $f_1=f_s$ with varied voltage (2V steps)

Neglecting some interferences between harmonic and intermodulation components at multiples of f_1 the intermodulation components d_2 and d_3 are almost constant for $f_2 > 3 f_s$. This is typical for drivers with dominant Bl(x) nonlinearity. The intermodulation distortion d_2 and d_3 rise monotonically with the terminal voltage. For a terminal voltage of $U_1=U_2$=1.3 V_{rms}, the fictitious driver produces already d_3= 10 %. This corresponds to a peak displacement X_{max}= 1.2 mm.

3.3 Measurement Setup

The loudspeaker modeling and numerical simulation shows that the combination of a harmonic and intermodulation distortion measurement provides essential information for defining X_{max} more clearly. A two-tone signal with fixed frequencies is an optimal stimulus that can be produced simply by two sinusoidal generators. Performing a series of measurements with varied frequencies f_1 and f_2 is not necessary but variations of the terminal voltage are required. This is a main difference from measurements of the linear transfer function where we expect the same response from the system at low and high amplitudes. For the bass tone f_1 the resonance frequency f_s is a distinct frequency giving high voice coil displacements, low input current and sufficient sound pressure level output at the lower end of the transfer band. The frequency of the voice tone f_2 is apparently not critical. The frequency of voice tone f_2 should be much higher than f_1 so it generates not much displacement but significant input current. To avoid interferences with harmonics of the fundamental frequency f_1, a fractional ratio f_2/f_1 =5.5 may be used between both tones. However, the IEC standard recommends $f_2 > 8f_1$ making the second order modulation distortion d_2 more sensitive to Doppler effect. The standard also suggest an amplitude ratio of $U_1=4*U_2$. Using the same amplitude for both tones $U_1=U_2$ would give similar values of the modulation distortion d_2 and d_3 but a much better signal to noise ratio for the intermodulation distortion, and would allow us to compare the harmonics of the bass and voice tone with each other. Although these modifications bring some advantages we will stay with recommended methods of IEC 60268.
To assess the output distortion we have to monitor the sound pressure signal. We recommend setting the microphone in the near field of the driver, close to the diaphragm, to avoid a free field acoustical environment. To find X_{max} we also have to measure the voice coil displacement precisely. A displacement meter is a indispensable tool for driver design. Laser sensors based on the triangulation principle are not much more expensive than a microphone and can also measure the DC displacement

component. It is also recommended to monitor the input current by using a shunt or current sensor.
A FFT analysis of the measured state variable *y(t)* provides the fundamentals $Y(f_1)$, $Y(f_2)$, harmonics of bass and voice tone $Y(kf_1)$ and $Y(kf_2)$, and the sum- and difference-tone intermodulation $Y(f_2 \pm kf_1)$ of order k. In addition to the distortion measures d_t, d_2 and d_3, we recommend also calculating separated second-order harmonic distortion

$$d_{h2} = \frac{Y(2f)}{\sqrt{Y(f)^2 + Y(2f)^2 + Y(3f)^2 + \ldots + Y(kf)^2}} * 100\ \%$$

and third-order harmonic distortion

$$d_{h3} = \frac{Y(3f)}{\sqrt{Y(f)^2 + Y(2f)^2 + Y(3f)^2 + \ldots + Y(kf)^2}} * 100\ \%$$

These measures show the effect of symmetrical and asymmetrical parameter variation more analytically.

3.4 Dominant Source of Distortion

Applying the methods of IEC 60268 to the spectral components of sound pressure, displacement and current, we get a set of distortion measures described in Table II.

DISTORTION MEASURES	INTERPRETATION
X_{DC}	The DC part in the displacement is generated dynamically by signal rectification due to parameter asymmetries. The DC part X_{DC} generated by the two-tone signal is mainly caused by suspension asymmetries shifting the coil always towards the minimum of the nonlinear stiffness curve $K_{ms}(x)$.
$d_{h2,f1}$	The second-order harmonic distortion considering sound pressure component $P(2f_s)$ is a good indicator for asymmetrical stiffness $K_{ms}(x)$. It also reflects some effects of asymmetrical force factor $Bl(x)$. It is insensitive to the nonlinear inductance $L_e(x)$ because the amplitude of the current is low at the resonance.
$d_{h3,f1}$	The third-order harmonic distortion considering sound pressure component $P(3f_s)$ is a good indicator for symmetrical variations of the stiffness $K_{ms}(x)$. It partly reflects the symmetrical variations of force factor $Bl(x)$. It is insensitive to the nonlinear inductance $L_e(x)$ because the amplitude of the current is low at the resonance.
d_2	The second-order intermodulation distortion considering sound pressure components $P(f_2 \pm f_1)$ is a good indicator for asymmetrical variations of inductance $L_e(x)$, of force factor $Bl(x)$ and Doppler effect. The effect of asymmetries in stiffness $K_{ms}(x)$ is negligible.
d_3	The third-order intermodulation distortion in sound pressure considering $P(f_2 \pm 2f_1)$ is a good indicator for symmetrical variations of force factor $Bl(x)$ due to the limited voice coil height. The effects of the other nonlinearities such as inductance $L_3(x)$, stiffness $K_{ms}(x)$ and Doppler effect are negligible.
$d_{2,i}$	The second-order intermodulation distortion considering current components $I(f_2 \pm f_1)$ is a good indicator for asymmetrical variations of inductance $L_3(x)$. The effect of the other nonlinearities such as force factor $Bl(x)$, stiffness $K_{ms}(x)$ and Doppler effect are negligible.
$d_{3,i}$	The third-order intermodulation distortion considering current components $I(f_2 \pm f_1)$ is a good indicator for symmetrical variations of inductance $L_3(x)$. The effects of the other nonlinearities such force factor $Bl(x)$, stiffness $K_{ms}(x)$, Doppler and radiation are negligible.
$d_{h2,f2}$	The second-order harmonic distortion considering sound pressure component $P(2f_2)$ is a good indicator for the reluctance force due to asymmetrical inductance $L_e(x)$. It also reveals flux modulation due to the asymmetrical variation of the $Bl(i)$ versus voice coil current *i* and other non-linearities in the driver (partial vibration in the diaphragm, etc.). This measurement is insensitive to variations of force factor $Bl(x)$ and stiffness $K_{ms}(x)$ versus displacement and Doppler effect.
$d_{h3,f2}$	The third-order harmonic distortion in sound pressure at $P(3f_2)$ is good indicator for flux modulation due to the symmetrical variation of the $Bl(i)$ versus voice coil current *i*. It also reflects some other minor nonlinearities in the driver (partial vibration in the diaphragm, etc.). This measurement is insensitive to variations of force factor $Bl(x)$, stiffness $K_{ms}(x)$ and inductance $L_e(x)$ versus displacement and Doppler effect.

Table II: Distortion measures based on two-tone signal

Physical Cause	X_{DC}	$d_{h2,f1}$	$d_{h3,f1}$	d_2	d_3	$d_{2,i}$	$d_{3,i}$	$d_{h2,f2}$	$d_{h3,f2}$
Coil offset and asymmetry of Bl(x)		**X**		**X**					
Coil height			**X**		**X**				
Asymmetry in suspension	**X**	**X**							
Symmetrical limiting of suspension			**X**						
Asymmetry in $L_e(x)$				**X**		**X**			
Symmetrical variation in $L_e(x)$					x		x		
Reluctance Force								x	
Flux modulation								x	x
Doppler				**X**					
Nonlinear Radiation				x	x				
Partial Cone Vibration								x	x

Table III: Relationship between nonlinearities and distortion measures (bold symbols represent significant distortion)

The distortion measurements listed in Table II give some clues about the physical causes that limit peak displacement X_{max}. The relationships are represented by crosses in Table III . The dominant non-linearities caused by the force factor *Bl(x),* inductance $L_e(x)$ and compliance $C_{ms}(x)$ of the mechanical suspension and the Doppler effect may produce substantial values of distortion (greater 5 %). They are the limiting factors of X_{max} in common transducers and are emphasized by bold crosses. The variation of the radiation conditions cause relatively small distortion for frequencies below 1 kHz. The other nonlinearities such as flux modulation and partial cone vibration produce much less distortion in common transducer.

The usage of Table III is quite simple. A driver having significant values of $d_{h2,f1}$ and d_2 suffers from *Bl*-asymmetry caused by a coil offset or field geometry. If a high value of d_2 coincides with significant $d_{2,i}$ in the input current then the asymmetry of the inductance $L_e(x)$ should be reduced by using a short cut ring or copper cap. The Doppler effect can be easily identified by getting a high value of d_2 coupled with a low value of $d_{2,i}$. An asymmetrical suspension can easily be detected by high values of $d_{h2,f1}$ and significant X_{DC} while the other second-order distortion are small.

3.5 New X_{max} Definition

Summarizing the considerations we may suggest the wording of the X_{max} definition:

X_{max} is the voice-coil peak displacement at which the maximal value of either the total harmonic distortion d_t or the 2nd order modulation distortion d_2 or the 3rd-order modulation distortion d_3 in the radiated sound pressure is equal to a defined threshold (d=10 %). The driver is operated in free air and is excited by the linear superposition of a first tone at the resonance frequency $f_1=f_s$ and a second tone $f_2=8.5\ f_s$ with an amplitude ratio of 4:1. The total harmonic distortion d_t assesses the harmonics of f_1 and the modulation distortions are measured according to IEC 60268 in the near field of the driver. Manufacturer shall state X_{max}, the dominant type of distortion (d_t, d_2 or d_3) and the value of the threshold d used.

3.6 Practical Use

1. Measure the resonance frequency f_s of the driver.
2. Excite the driver under voltage drive with a two-tone signal at $f_1=f_s$ and $f_2=8.5\ f_s$ with an amplitude ratio of 4:1.
3. Perform a series of measurement while increase the input amplitude and measure the peak voice coil displacement and the sound pressure in the near field of the driver. Perform a spectral analysis of the sound pressure signal and determine the total harmonic distortion and intermodulation distortion according IEC 60268.
4. Search for the minimal value of the peak displacement where either d_t, d_2 or d_3 are equal to the threshold d.
5. State the peak displacement X_{max}, and the type of distortion limiting the excursion.

For example, a statement

X_{max}= 3.8 mm @ d_2=10 % (d_t, d_3 < 10 %)

means that a driver provides a maximal peak displacement of X_{max}=3.8 mm where the 2nd-order modulation distortion is dominant and produce the threshold of 10 % distortion. This statement implies that the total harmonic distortion and 3rd-order distortion are less than 10 % which can be added in parenthesis optionally. Thus the suspension and the voice-coil height are most likely not the limiting factors for the excursion of this driver.

4 Parameter-based Method

Although the performance-based method gives some indication about the dominant source of distortion this approach fails in assessing the limiting factors of each nonlinearity quantitatively. This information is required when the driver designer would like to improve the maximal output of the driver while keeping the cost and other parameters constant. The system designer also needs this data to select a driver which produces distortion at X_{max} that are acceptable for his particular application (subwoofer, woofer or full-band system). The parameter-based method provides a separate value of maximal displacement for each driver nonlinearity which is of practical interest. To avoid any confusion with the performance-based method these values are called *Displacement limits*. The nonlinearity with the smallest value will limit the peak displacement of the driver finally. The parameter-based method also uses threshold which should be defined consistent with the thresholds in the current X_{max} definition to provide comparable results.

4.1 Displacement Limits due to Driver Nonlinearities

The maximal voice coil displacement 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 $L_e(x)$, $L_2(x)$ and $R_2(x)$ nonlinearity,
- X_D represents tolerable distortion due to Doppler nonlinearity.

4.1.1 Displacement Limit X_C

The maximal displacement related to the critical mechanical strain of suspension may be obtained from the nonlinear stiffness characteristic $K_{ms}(x)$ or from its counterpart, the compliance characteristic $C_{ms}(x)$. Clark [7] suggested to evaluate the variation of this nonlinear parameters. Following his proposal, we introduce a minimal compliance ratio

$$C_{\min}(X_C) = \min_{-X_C<x<X_C}\left(\frac{C_{MS}(x)}{C_{MS}(0)}\right) * 100\,\%$$

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}.
The large signal identification implemented in the Distortion Analyzer 1 [8] determine the safe range of operation automatically by comparing the C_{min} value with a user-defined protection limit C_{lim}. This parameter is easy to use, and it has proven to be a reliable measure for determining the critical mechanical strain affecting the suspension.

4.1.2 Displacement Limit 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.

4.1.3 Displacement Limit 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

$$Bl_{\min}(X_{Bl}) = \min_{-X_{Bl}<x<X_{Bl}}\left(\frac{Bl(x)}{Bl(0)}\right)*100\%$$

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}.

4.1.4 Displacement Limit X_L

The electrical impedance $Z_e(f, x)$ of the driver above the resonance frequency depends on the frequency and the displacement of the coil. Fig. 11 shows the magnitude of the electrical impedance versus frequency f for three voice coil positions X= -7, 0, +7 mm. The increase of the impedance for a negative displacement and the decrease for positive displacement is typical for drivers having no short cut ring or copper cap on the pole piece.
The complicated frequency characteristic is caused by the para-inductance of the coil and additional losses due to eddy currents. This can be modeled by a lumped parameter model comprising the electrical DC resistance R_e, the voice coil resistance $L_e(x)$ and the additional elements $L_2(x)$ and $R_2(x)$ in parallel. For the nonlinear elements we assume the same shape of the curve giving

$$\frac{L_e(x)}{L_e(0)} = \frac{L_2(x)}{L_2(0)} = \frac{R_e(x)}{R_e(0)}.$$

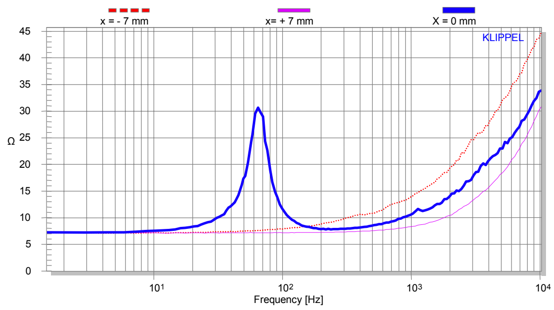

Fig. 11: Electrical Impedance of the free moving coil at the rest position and the coil at maximal positive and negative displacement with blocked movement.

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

$$Z_{\max}(X_L) = \max_{-X_L<x<X_L}\frac{|Z_e(x,f_2)-Z_e(0,f_2)|}{|Z_e(0,f_2)|}*100\ \%$$

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 and the impedance can be approximated by

$$Z_e(x, f_2) \approx R_e + L_e(x)s_2 + \frac{R_2(x)L_2(x)s_2}{R_2(x) + L_2(x)s_2}$$

where $s_2=2\pi f_2 j$.

4.1.5 Displacement Limit X_D

The peak displacement X_D considering the audibility of the Doppler effect can be calculated analytically using the simple equation

$$X_{peak} = \frac{770\ d_2}{f_2}$$

presented by Beers and Belar [9], using the peak displacement X_{peak} in mm, the second-order modulation distortion d_2 in percent according to IEC 60268 and the frequency f_2 of the modulated voice tone. To keep the definition of X_D consistent with the performance base method we set $f_2=8.5\ f_s$ and use the distortion threshold d (d=10%) giving a displacement limit due to Doppler

$$X_D = \frac{90.5d}{f_s}$$

where X_D is in mm and f_s is in Hz.

4.2 Practical Use

1. Measure the small signal parameters such as resonance frequency f_s, DC voice coil resistance R_e, resistance $R_2(0)$ and inductance $L_2(0)$ at $x=0$.
2. Measure the nonlinear characteristics compliance $C_{ms}(x)$, force factor $Bl(x)$, and inductance $L_e(x)$ versus displacement x. Listen for excessive distortion and assign $X_{clip}=X_{peak}$ in case of mechanical clipping.
3. Determine the peak displacement X_c, X_{Bl}, X_L and X_D by using the nonlinear characteristics and thresholds for C_{min}, B_{min}, Z_{max} and d.
4. State the displacement limits X_c, X_{Bl}, X_L, X_{clip} and X_D together with the thresholds C_{min}, B_{min}, Z_{max} and d used.

5 Definition of Thresholds

Both the peak displacement X_{max} from the performance-based method and the displacement limits X_c, X_{Bl}, X_L, X_{clip} from the parameter-based method depend on thresholds. These thresholds should consider the audibility of the distortion components, the maximal mechanical load and should lead to comparable results in both methods.

5.1 Audibility

The new performance-based method uses the old distortion threshold d = 10 % for the maximal harmonic distortion. This value is also applied for the second- and third-order intermodulation distortion. At current time there are no better arguments for using other values. The audibility of the nonlinear distortion generated by loudspeakers depend on the following factors:

- Linear driver parameters (resonance frequency f_s and loss factor Q_{ts})
- Driver nonlinearities (*Bl(x), Le(x), Cms(x)* and Doppler)
- System application (crossover frequency, type of enclosure)
- Excitation signal (Nature, bandwidth, spectral and temporal complexity)
- Audible acuity of a listener

For example, a suspension nonlinearity produces distortions confined to frequencies about the resonance. Contrary, $Bl(x)$ and $L_e(x)$ nonlinearities produce substantial intermodulation throughout audio band which might be tolerable in subwoofer applications. Thus the evaluation of the nonlinear distortion is a complex issue. Digital transducer modeling gives new possibilities for combining subjective and objective investigations by operating the loudspeaker under normal conditions and using ordinary music or any other signal as stimulus. Auralization techniques [10] are the basis for systematic listening tests providing more reliable data in the near future.

5.2 Relationship between Thresholds

The thresholds C_{min}, , Bl_{min}, Z_{max} and d used in the parameter–based approach should be consistent with the distortion thresholds of performance-based approach. Numerical techniques based on the loudspeaker model allows to simulate the sound pressure output for some typical shapes of driver nonlinearities and to calculate parameter ratio B_{min},C_{min} and Z_{max} that correspond with distortion threshold d=10% as shown in Table IV. A short and long voice coil overhang is simulated by a power series expansion of Bl(x) using a quadratic and a fourth-order term, respectively. We assume that there are no asymmetries in the Bl(x) characteristic. A nonlinear compliance $C_{ms}(x)$ having a quadratic term represents a progressive spider. The fourth-order term describes the symmetrical limiting of the surround. A severe asymmetry such as caused by cup spider can be modeled by a power series of $C_{ms}(x)$ truncated after the linear term. A typical inductance characteristic can also be approximated by a linear power series expansion.

Example	Nonlinear Parameter	Parameter Threshold	Distortion Threshold
Motor with Equal-length configuration	$Bl(x)=b_0+b_2x^2$	$Bl_{min}\approx$ 82 %	d_3= 10 %
Motor with large coil overhang	$Bl(x)=b_0+b_4x^4$	$Bl_{min}\approx$ 82 %	d_3= 10 %
Progressive spider	$C_{ms}(x)=c_0+c_2x^2$	$C_{min}\approx$ 74 %	d_t= 10 %
Linear spider with limiting surround	$C_{ms}(x)=c_0+c_4x^4$	$C_{min}\approx$ 77 %	d_t= 10 %
Asymmetry in suspension	$C_{ms}(x)=c_0+c_1x$	$C_{min}\approx$ 78 %	d_t= 10 %
Typical inductance characteristic	$L_e(x)=l_0+l_1x$	$Z_{max}\approx$ 10 %	d_2=10%

Table IV: Minimal parameter variation generating 10 % distortion in the radiated sound pressure.

A second-order and fourth-order nonlinearity produces 10 % distortion at similar values of the parameter variation (about 82 % for $Bl(x)$ and about 75 % for $C_{ms}(x)$). However, a higher order non-linearity will produce much less distortion at lower displacement $|X| < X_{max}$ than a parabola shaped curve. Thus, the nonlinear parameters themselves are required to predict the distortion versus amplitude, and to explain the benefit of a motor with a larger voice coil overhang over an equal-length configuration.

5.3 Admissible Mechanical Load

The threshold C_{min}=75% producing d_t=10% distortion seem to be relatively high compared with the mechanical load admissible to most drivers. In the Distortion Analyzer system, a minimal compliance ratio C_{min} = 50 % is used as a default protection parameter. Most common suspension systems will stand variation down to a C_{min}= 20 % for some period of time without causing any damage.

It is also possible that manufacturers define admissible thresholds that seem proper for their particular products and specify these values as measurement conditions along with the displacement limits.

6 Practical Examples

Both the performance-based and parameter-based methods will be applied to two real drivers to illustrate both techniques. The first driver A has an extremely long voice coil coupled with a limited suspension. By contrast, the second driver B uses a short coil with a very linear suspension. The nonlinear parameters are measured dynamically by using the Distortion Analyser.

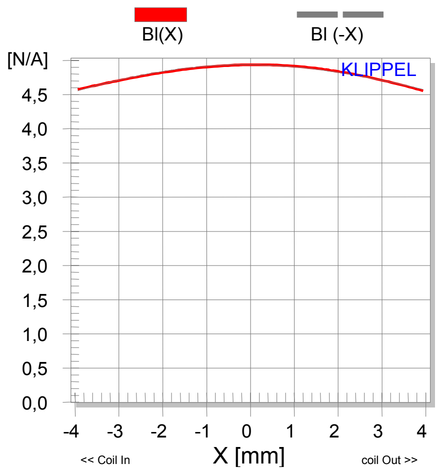

Fig. 12: Force factor $Bl(x)$ versus voice coil displacement x of driver A

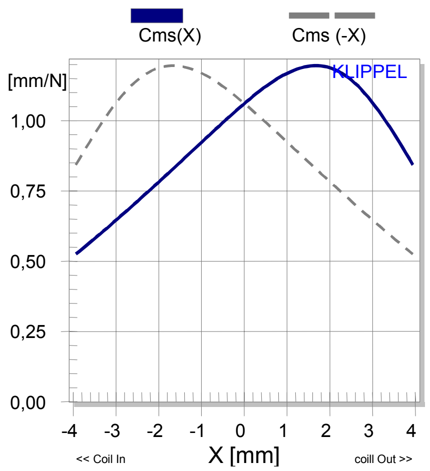

Fig. 13: Compliance $C_{ms}(x)$ of the mechanical suspension versus voice coil displacement of driver A

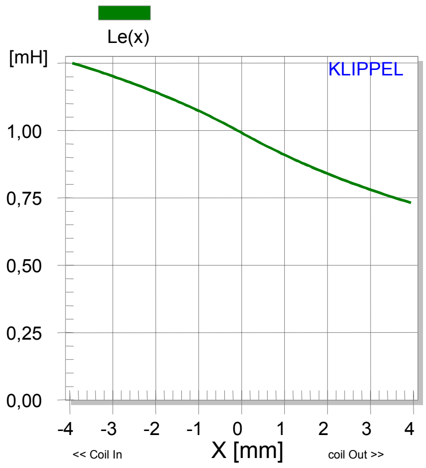

Fig. 14: Inductance $L_e(x)$ versus voice coil displacement x of driver A

6.1 Driver A

The force factor $Bl(x)$ in Fig. 12 remains almost constant over the measured range producing low modulation distortion. Considering a limit of B_{min} = 82 %, the admissible peak displacement X_B is beyond 4 mm. Apparently, the magnet field geometry is symmetrical and the coil is at the optimal rest position.

However, the compliance $C_{ms}(x)$ in Fig. 13 has a asymmetrical characteristic becoming obvious by comparing the regular curve $C_{ms}(x)$ with the mirror curve $C_{ms}(-x)$ presented as dotted line. Considering a limit value of C_{min}=75 %, the admissible peak displacement X_C is 2 mm. Due to the asymmetry, the suspension limits the excursion only at negative displacement.

Fig. 14 shows the asymmetric characteristic of the inductance $L_e(x)$, which is typical for a motor without shortcut ring or copper cap. Considering the resonance frequency f_s= 49 Hz, a DC resistance R_e = 6.8 Ω and the limit value Z_{max} = 10 %, the admissible peak displacement X_L exceeds the measured range of 4 mm.

The admissible peak displacement X_D producing 10 % modulation distortion is about 18 mm.

Searching for the minimum between the separate peak displacements X_B, X_C, X_L, X_D, clearly the suspension limits the maximal displacement to 2 mm approximately.

Using the new performance-based method the total harmonic distortion d_t, the second- and third-order modulation are measured versus peak displacement and presented in Fig. 15.

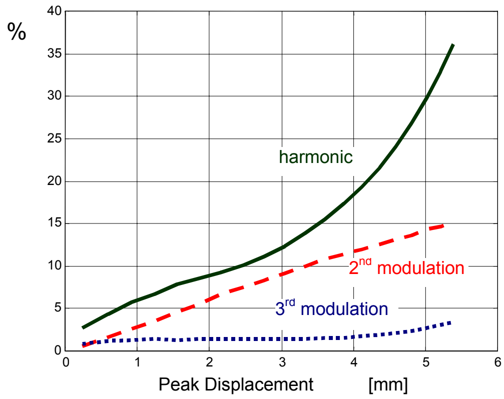

Fig. 15: Total harmonic distortion d_t,(solid line), second-order modulation d_2 (dashed line) and third-order modulation distortion d_3 (dotted line) versus peak displacement x of driver A

Since the suspension is the limiting factor, the total harmonic distortion dominates and exceeds the 10 % limit at X_{max}= 2.4 mm first. The second-order distortion caused by asymmetrical inductance $L_e(x)$, Doppler effect and Bl asymmetry cut the 10 % distortion level at 4 mm. The third-order distortion, which is directly related to the voice coil height and the symmetrical Bl variation, is far below 10 % up to 6 mm displacement.
Table V summarizes the other distortion measures determined at a $U_1=U_2=U_{10\%}$= 3. 4 V_{rms} giving a peak displacement of X_{max}= 2.4 mm.

	Speaker A	**Speaker B**
$f_1 = f_s$	50 Hz	44 Hz
$f_2=8f_1$	400 Hz	360 Hz
U @ d=10 %	3.4 V_{rms}	1.87 V_{rms}
X_{DC}	0.31 mm	0.03 mm
$d_{h2,f1}$	8.7 %	4.3 %
$d_{h3,f1}$	5.4 %	3.6 %
d_t	**10 %**	5.7 %
d_2	7.9 %	8.4 %
d_3	1.5 %	**10 %**
$d_{2,i}$	7.7 %	3.3 %
$d_{3,i}$	0.5 %	1.2 %
$d_{h2,f2}$	0.58 %	0.4 %
$d_{h3,f2}$	0.34 %	0.4 %
X_{max} @ d= 10%	2.4 mm	2.1 mm

Table V: Results of the performance-based method

The second-order harmonic distortion $d_{h2,f1}$ = 8.7 % of the bass tone f_1 dominates the third-order harmonic $d_{h3,f1}$ = 5.4 % due to the substantial asymmetry of the suspension. The positive DC-displacement generated by rectification of the bass tone shifts the coil in positive direction where the compliance is maximal. Thus, improving the symmetry of the curve will give more X_{max}.
The second-order distortion d_2 in sound pressure and $d_{2(I)}$ in current are in the same order of magnitude, indicating that the inductance asymmetry is the physical source while the contribution of Bl-asymmetry and Doppler is much smaller. The harmonic distortions of the voice tone reveal the effect of nonlinearities that are related to voice coil current or mechanical stress in the diaphragm. However, the distortion measures $d_{h2,f2}$, $d_{h3,f2}$, $d_{3,i}$ are as usual below 1 %, which can be neglected in comparison to the dominant nonlinearities.
The most important information may be stated by the manufacturer:

X_{max} = 2.4 mm @ d_t =10 % (d_2, d_3 < 10 %)
X_C = 2 mm @ C_{min}=75 %
X_B > 4 mm @ Bl_{min}=82 %
X_L > 4 mm @ Z_{max}= 10%
X_D = 18 mm @ d_2= 10 %

6.2 Driver B

For a second speaker B we measured the following parameters

X_{max} = 2.1 mm @ d_3 =10 % (d_2, d_t < 10 %)
X_C > 4 mm @ C_{min}=75 %
X_B = 1.8 mm @ Bl_{min}=82 %
X_L > 4 mm @ Z_{max}= 10 %
X_D = 20.5 mm @ d_2= 10 %.

In contrast to speaker A we find dominant third-order intermodulation limiting the peak displacement Xmax. It corresponds with dominant force factor nonlinearity causing the lowest displacement limit X_B= 1.8 mm. The suspension, the inductance and the Doppler effect give much more excursion capabilities that cannot be used.

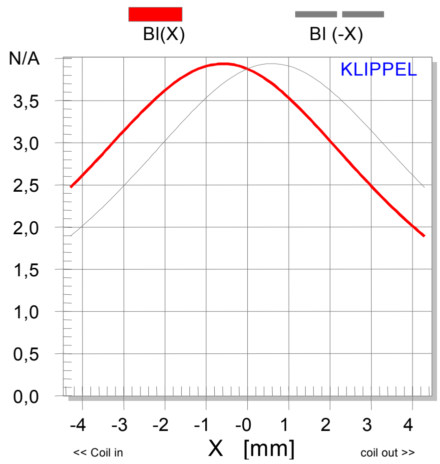

Fig. 16: Force factor $Bl(x)$ versus voice coil displacement of driver B

The force factor $Bl(x)$ as displayed in Fig. 16 reveals a short voice coil with low overhang. Such types of speakers are sensitive to an offset of the coil. Since the optimal rest position is 0.8 mm inside we have an asymmetrical characteristic. Considering the limit of B_{min}= 82 % for the decay of $Bl(x)$, we get a peak displacement of X_B = 1.8 mm related to the motor capabilities.
The compliance $C_{ms}(x)$ in Fig. 17 reveals a very linear suspension. The $C_{ms}(x)$ stays in the measured range above C_{min}=75 % (X_C > 4 mm).
Similar to driver A, the inductance $L_e(x)$ in Fig. 18 has the typical shape with a maximum at negative displacement. However, the absolute value of inductance is less than a third of driver A. Considering the resonance frequency f_s= 44 Hz and the DC resistance R_e = 3.8 Ω and the limit value of Z_{max} = 10 % the peak displacement X_L exceeds 4 mm.
Considering the Doppler effect, we get a peak displacement X_D = 20.5 mm.

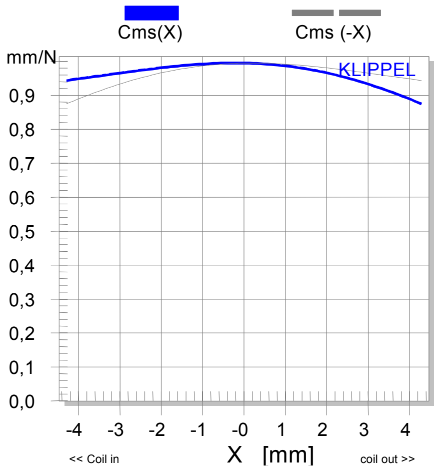

Fig. 17: Compliance $C_{ms}(x)$ of the mechanical suspension versus voice coil displacement x of driver B

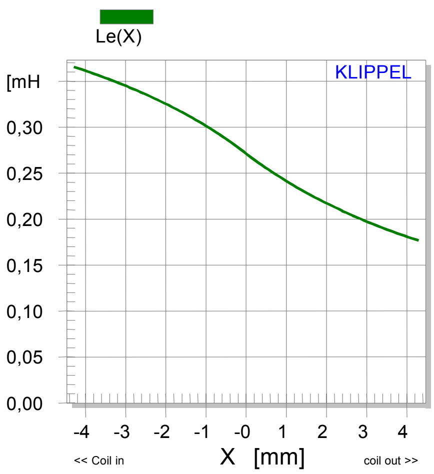

Fig. 18: Inductance $L_e(x)$ versus voice coil displacement x of driver B

Despite the asymmetry of the Bl(x)-curve which is not considered in the definition of the threshold Bl_{min}, the results of the parameter-based approach agree well with the results of the performance-based method. Fig. 19 shows the distortion d_t, d_2 and d_3 versus peak displacement X_{peak} measured with the two-tone signal.

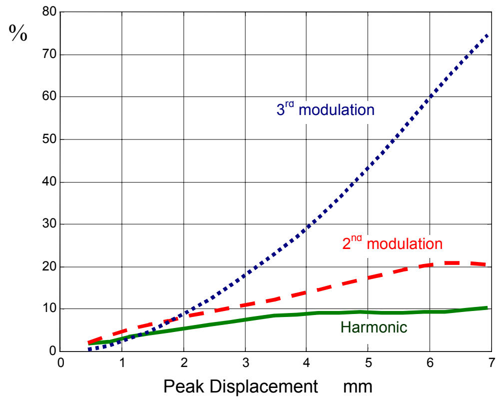

Fig. 19: Total harmonic distortion d_t (solid line), second-order modulation d_2 (dashed line) and third-order modulation distortion d_3 (dotted line) versus peak displacement x of driver B

Above 2 mm displacement the third-order modulation distortion d_3 becomes dominant and reaches the threshold of 10 % at X_{max} = 2.1 mm. Although the parameter-based method does not consider the shape of the nonlinear characteristic but only the crossing point at 82 % variation, we get similar results for X_{Bl}.
According to Table III significant values of d_3 show that the symmetrical Bl-variation due to a short coil limits the X_{max}. Considering the total harmonic distortion d_t only we would get much higher peak displacement X_{max}= 7 mm but at that X_{max} any voice tone will produce about d_3= 70 % modulation distortion. The second-order modulation distortion d_2 are twice of the harmonics. Additional measurement of the second-order modulation $d_{2(I)}$ in input current gives us more information about the source. Since d_2= 6.8 % in sound pressure is significant higher than $d_{2(I)}$ in current the force factor asymmetry gives a significant contribution.

7 Summary

The critical review of the numerical simulation on a fictitious loudspeaker and practical measurements on real loudspeakers show that the method in AES2-1984 does not provide a clear and useful definition of X_{max}. This is mainly caused by some ambiguities in the wording and more importantly by using assumptions, which are not valid in theory and practice. Clearly, the measurement of harmonic distortion is not sufficient for assessing all important aspects of the large signal performance as emphasized by Voishvillo [5]. Nonlinearities inherent in transducers such as force factor *Bl(x),* inductance $L_e(x)$ and Doppler produce significant modulation distortion. The current IEC standard 60268 provides all of the methods required for assessing these kinds of distortion and for defining X_{max} more clearly and reliably. The new definition is based on a two-tone measurement that can be accomplished with straightforward equipment. The resulting distortion measures are also valuable for transducer diagnostics to improve the driver design or select the optimal driver for the particular application.
The second part of the paper addressed an alternative method for assessing separate displacement limits closely related with the nonlinear driver parameters. In contrast to the performance-based approach, which measures some effects such as distortion of the nonlinear systems, the parameter-based method refers to the physical causes. The nonlinear curves and other linear parameters are summarized to a few numbers describing the limiting effect of each driver nonlinearity (Bl(x), Cms(x), L_e(x) and Doppler). This is a substantial data reduction where some particularities of the nonlinear curves are neglected. Despite the simplifications made in both methods the minimal value of the displacement limits X_{Bl} X_L, X_C, X_D is comparable with the peak displacement X_{max} derived from distortion measurement. Numerical tools are available for transforming and comparing the results of both methods.
Do both methods compete with each other and will the new parameter-based method eventually replace the performance-based method? I don't think so. It is a good idea to state X_{max} based on distortion measurements because it can easily be verified by simple equipment. The displacement limits X_B, X_C, X_L, X_D give additional information about the driver which are important for the system design.
The main target of this paper was the development of a framework for assessing the peak displacement more reliably. Both methods presented are still flexible by changing the thresholds used. This can be easily accomplished by an agreement between driver and system manufacturer considering special requirements. More long term testing of loudspeakers with instantaneous parameter monitoring and systematic listening tests using a digital transducer model will provide more information about assessable load and impact on sound quality. In the meantime the "traditional" threshold of 10 % distortion is a good starting point.

8 Acknowledgment

This paper is the result of many fertile discussions that I had with Alexander Voishvillo, David Clark and others.

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