LOUDSPEAKER NONLINEARITIES

CAUSES PARAMETERS SYMPTOMS

$K_{ms}(x)$ STIFFNESS VERSUS DISPLACEMENT

Loudspeakers use a suspension system to center the coil in the gap and to generate a restoring force which moves the coil back to the rest position. Only at low amplitudes there is an almost linear relationship between displacement x and restoring force F. The restoring force may be described by the product $F = K_{ms}(x)x$ of displacement x and stiffness $K_{ms}(x)$ varying with displacement.

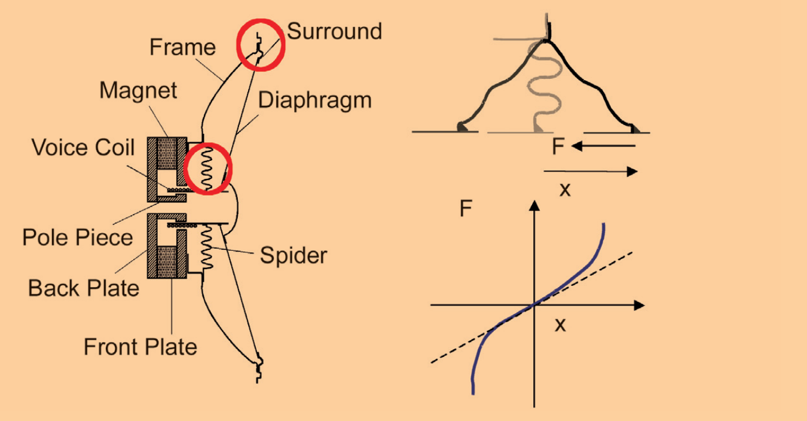

Figure 1: Suspension system in a conventional loudspeaker (sectional view) and the nonlinear force-deflection curve

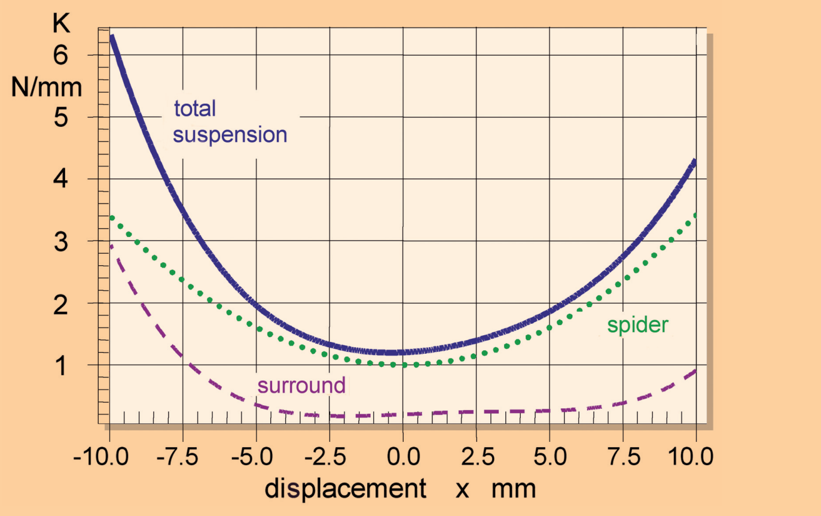

Figure 2: The total nonlinear stiffness $K_{ms}(x)$ of the driver suspension measured dynamically by using an audio-like stimulus. The properties of the suspension parts are identified by performing a second measurement of the driver after removing 80% of the surround.

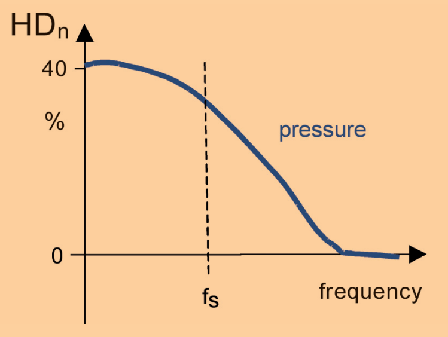

Figure 3: Nonlinear stiffness $K_{ms}(x)$ generates high harmonic distortion at low frequencies where voice coil displacement is high.

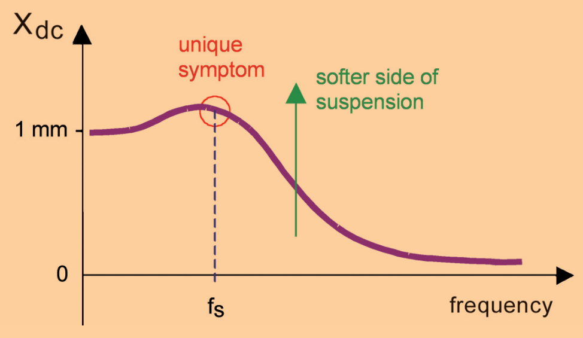

Figure 4: An asymmetric stiffness $K_{ms}(x)$ of the suspension generates a dc-displacement dynamically.

Symptoms

- high HD in sound pressure (for $f < 2f_s$)
- X_{dc} moves coil to softer side of stiffness curve
- at resonance ($f = f_s$):
  X_{dc} is dominated by $K_{ms}(x)$
- low IMD in sound pressure
- low HD and IMD in current

$Bl(x)$ FORCE FACTOR VERSUS DISPLACEMENT

The force factor Bl(x) describes the coupling between mechanical and electrical sides of an electro-dynamic transducer. It is the integral value of the flux density B over voice coil length l. The force factor Bl(x) is a function of voice coil displacement, depending on the geometry of the coil and the magnetic field generated by the magnet.

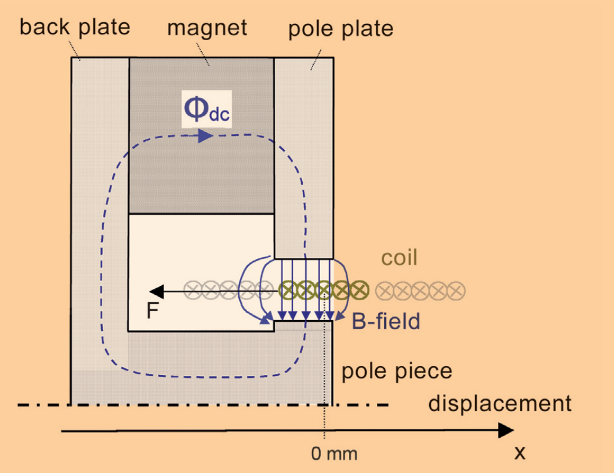

Figure 5: Voice coil current flowing in a static magnetic field generates an electro-dynamic force.

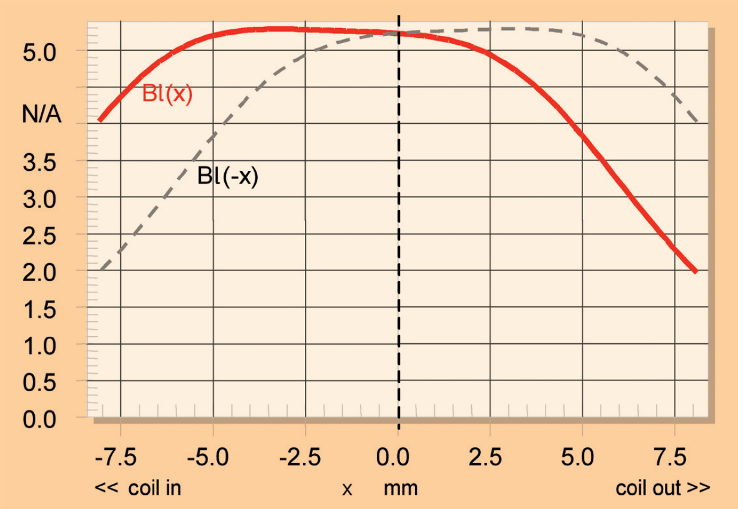

Figure 6: Force factor Bl(x) versus voice coil displacement x. The dashed curve represents the mirrored characteristic Bl(-x) to reveal the asymmetry of the nonlinearity.

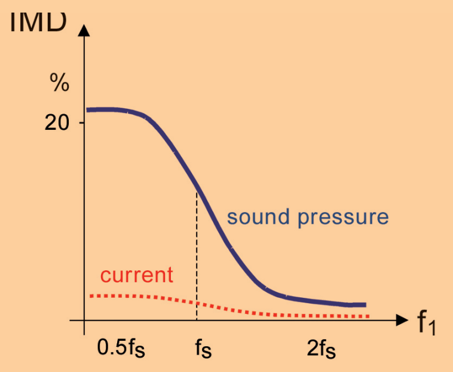

Figure 7: Characteristic frequency response of intermodulation distortion (IMD) in sound pressure output and input current caused by nonlinear force factor Bl(x) (using bass sweep technique with $f_2 = 20f_s$). The IMD decreases above resonance frequency f_s because the bass tone at f_1 produces less voice coil displacement.

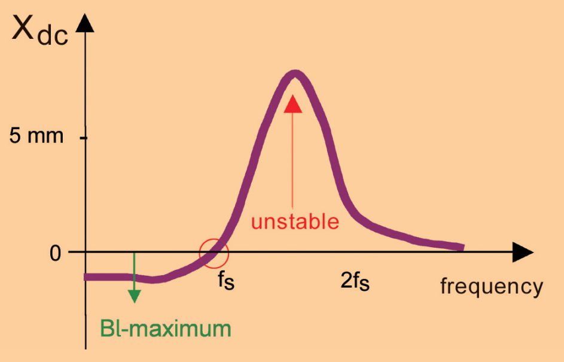

Figure 8: Typical response of dc-displacement X_{dc} versus frequency caused by a driver (in free air) with an asymmetric Bl-curve as shown in Figure 6

Symptoms

- high HD in sound pressure ($f < 2f_s$)
- high IMD in sound pressure ($f_1 < f_s$, $f_2 > f_s$)
- direction of X_{dc} varies with frequency:
  for $f < f_s$: small X_{dc} towards maximum of Bl-curve
  for $f = f_s$ (resonance): no dc-part generated ($X_{dc} = 0$)
  for $f > f_s$: X_{dc} away from Bl-maximum
  for $f \approx 1.5f_s$: high values of X_{dc}
  (→ may become unstable)
- low distortion in current

$L_e(x)$ INDUCTANCE VERSUS DISPLACEMENT

The current produces a magnetic ac-field which depends on the position of the coil. If the coil is in free air the magnetic flux is much lower than operating the coil in the gap where the surrounding iron path decreases the magnetic resistance. Current induced in the conductive material (shorting rings or caps made of aluminum or copper) as shown in Figure 9 generates a counter flux which reduces the total ac-flux significantly.

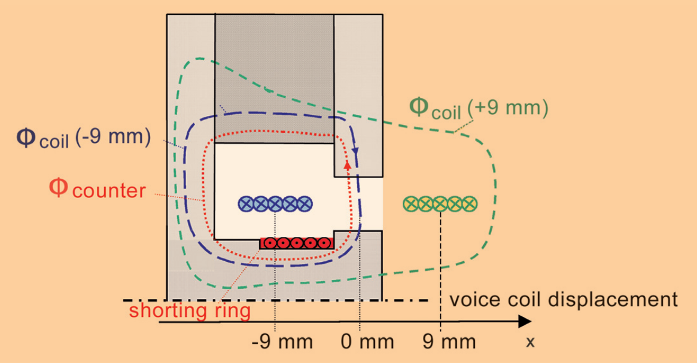

Figure 9: Magnetic ac-flux Φ_{coil} generated by the voice coil current for positive and negative displacement x of the coil and the counter flux $\Phi_{counter}$ generated by a shorting ring.

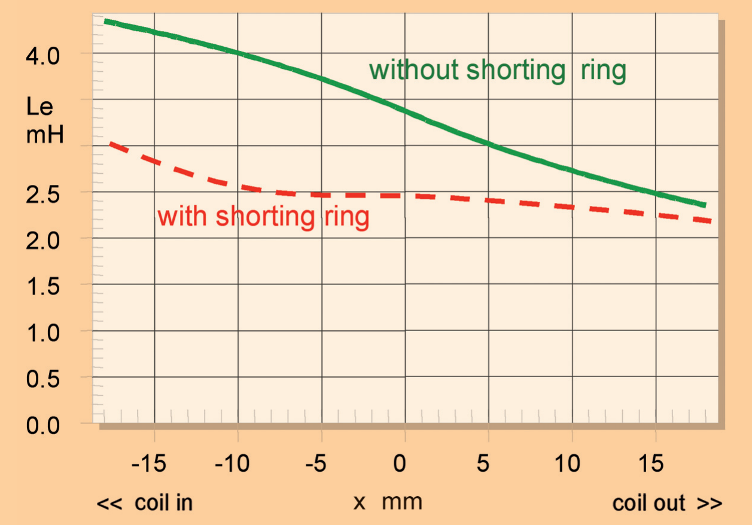

Figure 10: Placing the shorting ring below the gap reduces the voice coil inductance $L_e(x, i = 0)$ at negative displacement and gives an almost constant inductance.

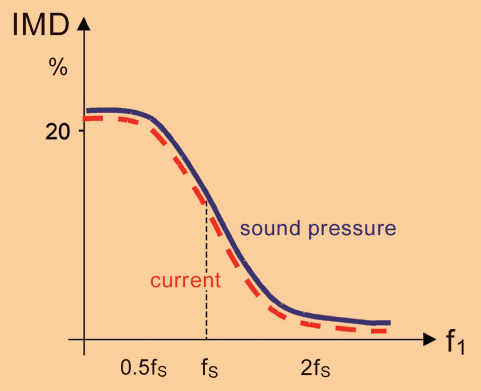

Figure 11: Inductance $L_e(x)$ varied by displacement causes the same characteristic frequency response as intermodulation distortion IMD measured in sound pressure and current. Above resonance the bass tone f_1 produces less displacement and the IMD decreases (bass sweep technique with $f_2 = 20f_s$).

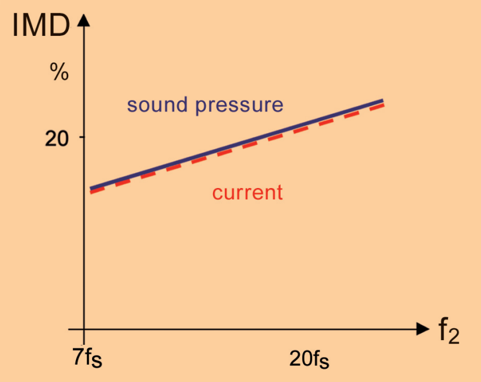

Figure 12: $L_e(x)$ generates IMD which rises by ≈6dB/octave with the frequency f_2 of the voice tone (voice sweep technique with $f_1 = 0.5f_s$).

Symptoms

- moderate HD in sound pressure and current for $1.5f_s < f < 4f_s$
- high IMD in sound pressure and current ($f_1 < f_s$, $f_2 > 7f_s$)
- small X_{dc} always towards the maximum of $L_e(x)$
- X_{dc} has a minimum at the resonance frequency f_s

$L_e(i)$ INDUCTANCE VERSUS CURRENT

Figure 13 illustrates the nonlinear relationship between magnetic field strength H and flux density (induction) B for three different voice coil currents. For i = 0 the magnet produces the field strength H_2 which determines the working point in the B(H)-characteristic. A high positive current (i = 10 A) increases the total field strength H_3 and operates the iron at higher saturation where the permeability is decreased. The variation of the permeability $\mu(i)$ causes a dependency of the inductance $L_e(x, i)$ on current i.

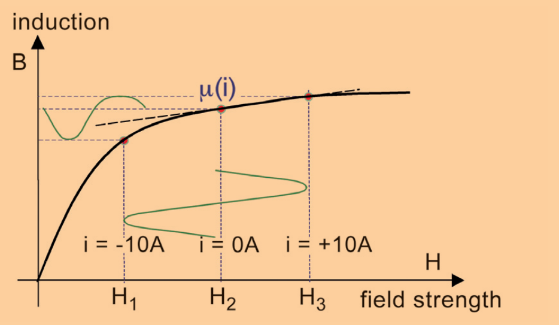

Figure 13: The nonlinear relationship between magnetic field strength H and flux density (induction) B in the iron material causes variation of the permeability μ(i) versus voice coil current i.

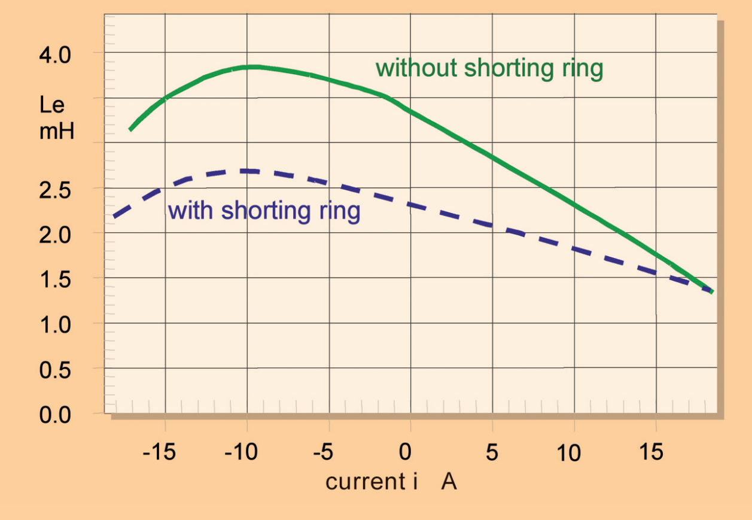

Figure 14: Voice coil inductance $L_e(i, x = 0)$ versus voice coil current i with and without shorting ring. Applying a shorting material also reduces „flux modulation" because the magnitude of the total ac-flux $\Phi_{ac}(i)$ is reduced.

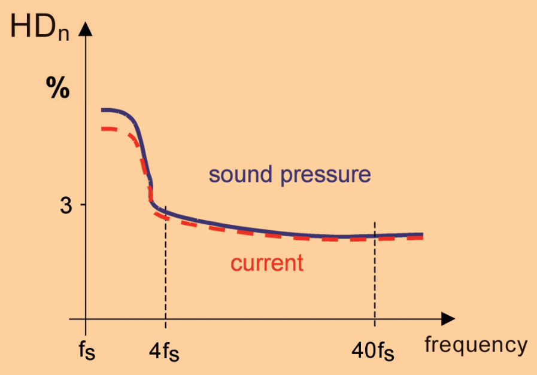

Figure 15: Current varying inductance $L_e(i)$ generates harmonic distortion (HD) at higher frequencies which are equal in sound pressure and current. The displacement varying nonlinearities (Bl(x), $K_{ms}(x)$ and $L_e(x)$) can not produce significant harmonic distortion (HD, THD) at those frequencies because the displacement is small.

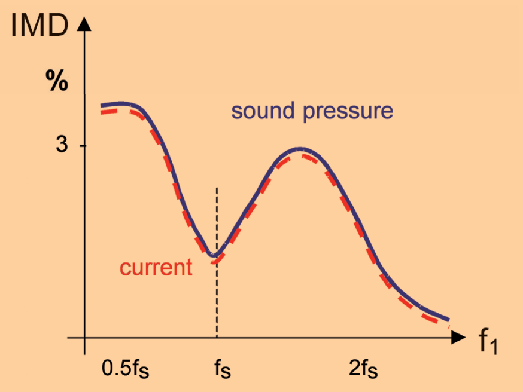

Figure 16: The current varying inductance $L_e(i)$ generates identical intermodulation distortion (IMD) in sound pressure and current. There is also a characteristic dip at resonance frequency f_s where the current is low (using bass sweep technique with $f_2 = 20f_s$).

Symptoms

- moderate HD in sound pressure and current ($f > 4f_s$)
- moderate IMD in sound pressure and current ($f_1 < 2f_s$, $f_2 > 7f_s$)
- for $f_1 = f_s$ IMD in sound pressure and current exhibits a minimum

LARGE SIGNAL MODEL

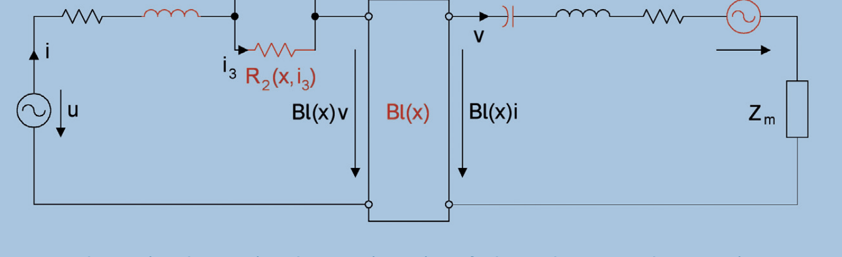

Figure 17: Electrical equivalent circuit of the electro-dynamic transducer. The dominant loudspeaker nonlinearities may be represented by lumped elements having varying parameters.

Lumped parameters:

- force factor Bl(x) of the electro-dynamical motor
- stiffness $K_{ms}(x)$ of the suspension
- voice coil inductances $L_e(x, i)$, $L_2(x, i)$
- resistance $R_2(x, i)$ due to losses from eddy currents
- dc-resistance $R_e(T_v)$ of voice coil
- impedance Z_m representing other mechanical and acoustical elements

State variables:

displacement x
velocity v
current i
voltage u
reluctance force $F_m(x, i, i_2)$
voice coil temperature T_v

EFFECT OF THE CURVE SHAPE

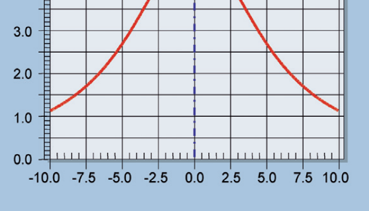

Figure 18:
Symmetrical Nonlinearity

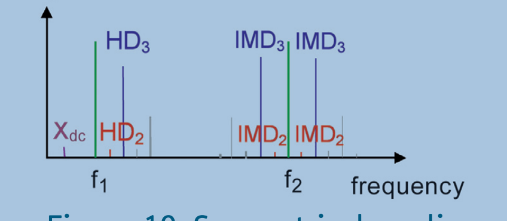

Figure 19: Symmetrical nonlinearity generates high 3rd-order distortion (HD_3, IMD_3).

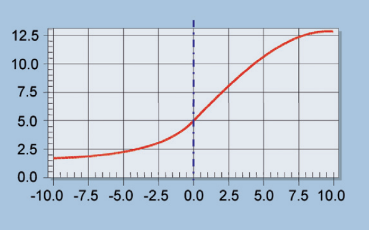

Figure 20:
Asymmetrical Nonlinearity

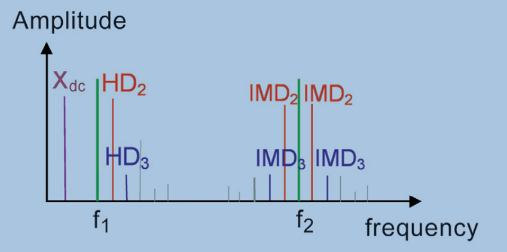

Figure 21: Asymmetrical nonlinearity generates high 2nd-order distortion (IMD_2, HD_2).

DISTORTION MEASUREMENT

using a two-tone stimulus ($f_1 << f_2$)

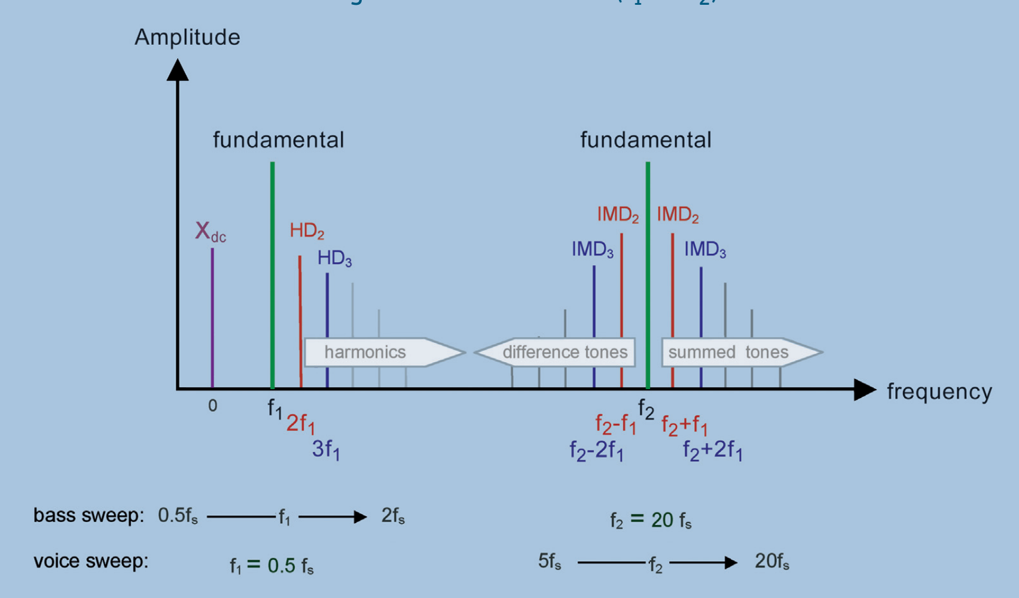

Figure 22: The intermodulation distortion is measured by varying the low frequency tone f_1 (bass sweep technique) or varying the high-frequency tone f_2 (voice sweep technique).

OVERVIEW OF SYMPTOMS

such as harmonic distortion (HD), intermodulation distortion (IMD), amplitude modulation distortion (AMD), dc-displacement (X_{dc}) generated by dominant loudspeaker nonlinearities.

Nonlinearities	SYMPTOMS GENERATED IN MONITORED STATE VARIABLE							
	Sound Pressure				Current			Displacement
	HD	*IMD* (bass sweep)	*IMD* (voice sweep)	*AMD* (voice sweep)	*HD*	*IMD* (bass sweep)	*IMD* (voice sweep)	X_{dc}
$K_{ms}(x)$ suspension (spider + surround)	X							X*
Bl(x) electro-dynamical motor	X	X	X	X				X*
$L_e(x)$ position of coil in the gap		X	X	X		X*	X	
$L_e(i)$ “flux modulation”	X	X	X	X	X*	X*	X	
Variation of Geometry of cone and suspension	X	X	X	X				
Young's-modulus $E(\varepsilon)$ of cone and suspension	X	X	X	X				
Flow resistance $R_A(v)$ in ports of vented enclosures	X							
Doppler Effect radiation of sound waves		X	X					
Wave Steepening sound propagation at high SPL	X		X					

*provides unique symptoms which are sufficent for the identification of the nonlinearity.

KLIPPEL

REFERENCE
step-by-step instructions (KLIPPEL Application Notes):

01 Optimal Voice Coil Position
02 Separating Spider and Surround
03 Adjusting the Mechanical Suspension
04 Measurement of Peak Displacement X_{max}
05 Displacement Limits due to Driver Nonlinearities
06 Measurement of Amplitude Modulation
07 Measurement of Weighted Harmonic Distortion HI-2
08 3D Intermodulation Distortion Measurement
09 3D Harmonic Distortion Measurement
10 AM and FM Distortion in Speakers
11 Check for Dominant Flux Modulation
12 Causes for Amplitude Compression
13 Dynamic Generation of DC-Displacement
14 Motor Stability
15 Checking for Compliance Asymmetry
16 Multi-tone Distortion Measurement
17 Credibility of Nonlinear Parameter Measurement
18 Thermal Parameter Measurement
19 Air Convection Cooling of Loudspeakers
20 Measurement of Equivalent Input Distortion
21 Reduce Distortion by Shifting Voice Coil
22 Rub & Buzz Detection without Golden Unit
23 Rub & Buzz Detection with Golden Unit
24 Measuring Telecommunication Drivers

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