Three curves calculated from the mechanical scanning data give the most condensed but almost comprehensive description of loudspeaker's small signal performance: The on-axis sound pressure response predicted in 1 m distance in the far field is depicted as a dotted line in Fig. 6. The thick line represent the sound power response of the loudspeaker and the thin line on the top shows with the accumulated acceleration level (AAL). The AAL corresponds with the total mechanical energy neglecting the phase information but normalized in such a way to be comparable with the acoustical output. It may be interpreted as the maximal acoustical sound pressure level while neglecting any acoustical cancellation. Therefore the AAL and SPL curves are identical at low frequencies (in Fig. 6 up to 800 Hz) where the loudspeaker cone vibrates in the rigid body mode and all points on the cone contribute to the sound pressure output constructively. However, at distinct frequencies such as 1.1, 4.4 and 7 kHz there are significant dips in the SPL output which are not found in the AAL. The difference between AAL and SPL curve describes the acoustical cancellation effect quantitatively. The AAL response comprises characteristic peaks which occur at the natural frequencies of the higher-order modes. The 3dB bandwidth of each "resonance peak" corresponds with the modal loss factor of the material used. At low frequencies the sound power response is most identical with both AAL and SPL responses because the loudspeaker dimensions are small compared to the wavelength and the radiator behave as an omni-directional source.

3. Regular Nonlinear Distortion

Table 2 gives an overview on the physical causes of regular nonlinear distortion affecting the loudspeaker's large signal performance [3]. The dominant nonlinearities are in the motor and suspension part of the electro-dynamical transducer because the voice coil displacement is relatively large compared to the dimensions of the coil-gap configuration and size of the corrugation rolls in the suspension (spider, surround). In micro-speakers, headphones and compression drivers the air flow in the gap may generate a nonlinear dependency of the mechanical resistance $R_{ms}(v)$ on velocity v. In vented-box loudspeaker systems there is a similar mechanism causing a nonlinear flow resistance $R_{ap}(v_p)$. High local displacement at the surround and a particular regions on the cone activate nonlinearities in the modal vibration. A typical nonlinearity related to the sound radiation is the Doppler Effect where the high excursion of the bass signal changes the position of the cone and causing variation in the propagation time affecting high frequency components radiated from the radiator at the same time. In horn compression drivers the high sound pressure causes a gradual steeping of the waveform while the sound wave is traveling from the throat to the mouth of the horn.

Causes of Nonlinear Distortion	**Measurements**	**Characteristics**
Nonlinear force factor Bl(x) and inductance $L_e(x)$, $L_e(i)$ of motor assembly (voice coil, iron path, magnet) Nonlinear stiffness $K_{ms}(x)$ of mechanical suspension (surround and Spider) Nonlinear losses $R_{ms}(v)$ of mechanical and acoustical system	Voltage and current at loudspeaker terminals, sound pressure in the near field of the driver	Nonlinear parameters and large signal parameters (e.g. voice coil offset) Nonlinear symptoms for particular stimuli IMD, X_{DC}, MTD, THD, Compression
Nonlinear flow resistance $R_{ap}(v_p)$ of the air in the port of a vented system	Sound pressure inside the vented enclosure	Compression of fundamental component at port resonance
Partial vibration of the radiator's surface	Sound pressure in near	THD, IMD, MTD

(surround, cone, diaphragm, dust cap)	or far field	
Doppler effect	Sound pressure in far field	IMD, MTD
Nonlinear sound propagation (wave steepening) in horns		IMD, THD, MTD

Table 2: *Overview on meaningful measurements for assessing the regular nonlinear signal distortion generated in loudspeaker systems and identifying their physical causes.*

The effect of the dominant nonlinearities can be investigated by the lumped parameter model shown in Fig. 7. Contrary to a linear model some elements have not a constant parameter but depend via a nonlinear function on voice coil displacement x, velocity v, current i, sound pressure in box enclosure p_{box} or other state variables.

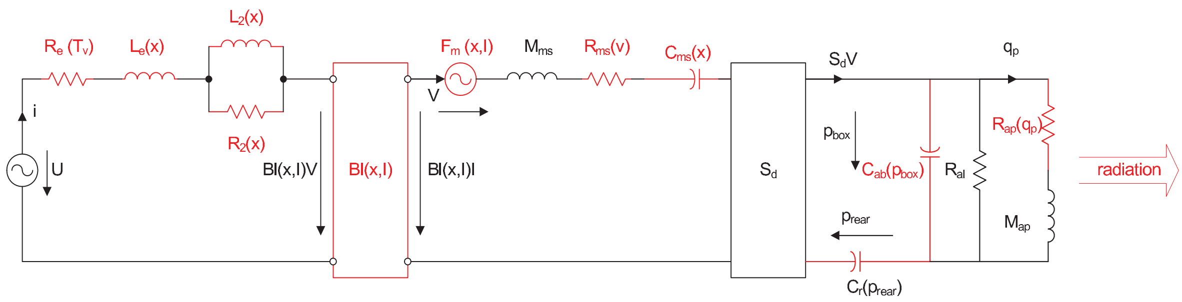

Figure 7: *Lumped parameter model of a vented-box loudspeaker system considering the dominant nonlinearities in the electrical, mechanical and acoustical domain.*

The shape of the nonlinear parameter characteristics are directly related to the geometry and properties of the material. Fig. 8 shows the nonlinear stiffness $K_{ms}(x)$ of the total suspension as the solid thick curve in the right diagram increasing at positive and negative displacements. This is very typical for any spider and surround when the shape of the corrugation rolls is deformed at high excursions.

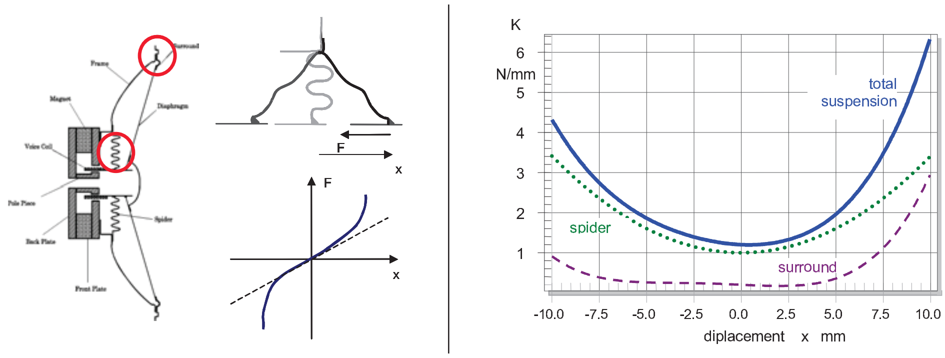

Figure 8: *Nonlinear stiffness characteristic K(x) versus displacement x of the mechanical suspension (surround and spider) dynamically measured by modern system identification using the electrical signals at loudspeaker terminals.*

The solid curve in Fig 8 also reveals an asymmetry in the stiffness characteristic which is caused by the asymmetrical shape of the surround which is more stiff and less compliant for positive than negative excursion. This asymmetry is an undesired property which causes not only 2nd- and higher-order distortion but generates a dc displacement moving the coil to the