Fast Measurement of Motor and Suspension Nonlinearities in Loudspeaker Manufacturing

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ABSTRACT

Nonlinear distortion are measured at the end of the assembling line to check the loudspeaker system and to make a pass/fail decision. However, the responses of single components and total harmonic distortion have a low diagnostic value because they are difficult to interpret and do not reveal the particular cause of the defect. A new measurement technique is presented which measures the nonlinearities of motor and suspension system directly. The results are single-valued parameters (e.g. voice coil offset in mm) which are directly related with the geometry and large signal parameters of the loudspeaker system. The measurement is only based on the measurement of the electrical signals at the speaker's terminals giving full robustness against ambient noise. The accuracy of the measurement results is investigated while performing measurements using short stimuli between 0.2 and 1.3 seconds. The paper discusses new possibilities for on-line diagnostic during end-of-line testing and the integration into production control to increase the yield of the production.

1. INTRODUCTION

Automatic testing at the end of the assembling line is performed to find loudspeaker defects caused by parts or the manufacturing process. Measurements of 2nd-order, 3rd-order and total harmonic distortion reveal symptoms of nonlinearities inherent in the loudspeaker. However, those measurements are difficult to interpret: For example, a high 2nd-order harmonic component gives only indications about a strong asymmetry in the nonlinear curve shape but it neither reveals the particular nonlinearity nor the problem in the manufacturing process. Both an offset in the voice coil rest position and variation in the geometry of the suspension part as illustrated in Fig 1 may contribute to second-order distortion [1].

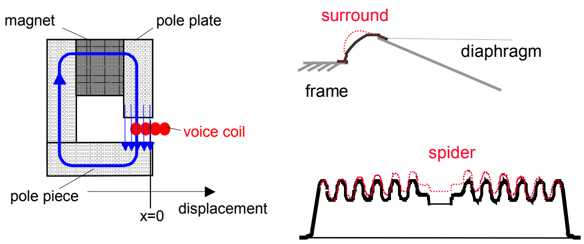

Fig 1: Loudspeaker nonlinearities caused by manufacturing: Offset in the voice coil rest position (left) and variation of the suspension geometry (right)

The dominant nonlinearities force factor $Bl(x)$, stiffness $K_{ms}(x)$ and inductance $L(x)$ can be measured dynamically by using nonlinear system identification technique which is defined in the IEC loudspeaker standard [2]. The first measurement system based on this technology uses an adaptive nonlinear system implemented in a digital signal processor (DSP) and is known as Large Signal Identification (LSI) [3].

The LSI dispenses with any additional sensor (microphone or laser) and is capable of using ordinary music as stimulus. This is very useful for long-term power testing where loudspeaker parameters variations are monitored and ageing of the suspension is investigated. However, the LSI is relatively slow and needs about 5 min for the initial identification of the loudspeaker parameters.

Quality control and end-of-line testing on 100% of the units requires a faster technique which accomplish a complete motor and suspension check within a few seconds or less. The result of this new measurement technique (in the following paper abbreviated by MSC) should be not curves describing the shape of the nonlinearity but single-valued numbers which are better suited for statistical analysis and more easy to interpret [4].

This paper describes the theory and implementation of a new measurement technique and shows practical application in quality control and end-of-line testing.

2. MEASUREMENT PRINCIPLE

2.1. Loudspeaker Modeling

The new technique used for the MSC is also based on nonlinear loudspeaker modeling and system identification.

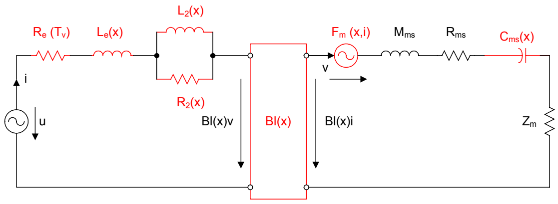

Fig 2: Electro-mechanical equivalent circuit of a drive unit

Fig 2 shows the equivalent circuit of a loudspeaker drive unit using lumped elements such as force factor *Bl(x)* of the motor,

- compliance $C_{ms}(x, t)$ of the suspension,
- voice coil inductance $L_e(x)$, $L_2(x)$, resistance $R_2(x)$ due to eddy currents, dc-resistance $R_e(T_V)$,
- reluctance force $F_m(x)$,
- moving mass M_{ms}.

Some parameters are not constants but depend on state variables such asdisplacement *x*,

- current *i*,
- Voice coil temperature T_V, electrical voltage *u* at the terminals,electrical current *i* at the terminals,The displacement varying

parameters *Bl(x)*, Compliance $C_{ms}(x)$ which is the inverse of the stiffness $K_{ms}(x)$ and the inductance $L_e(x)$ are the dominant nonlinearities in drive units.

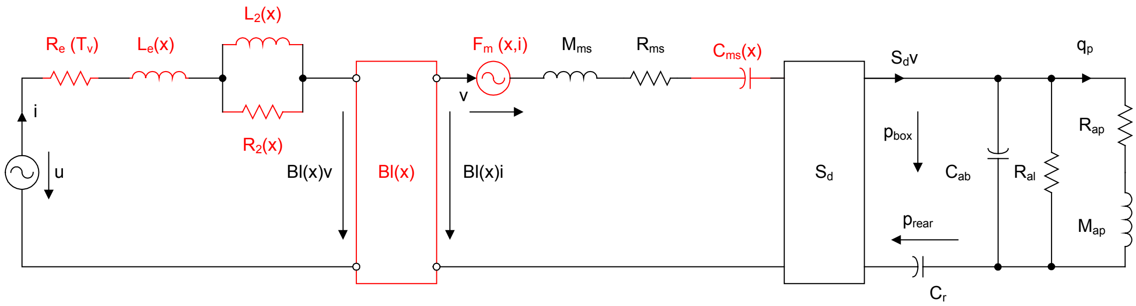

Fig 3: Electro-mechanical equivalent circuit of a vented-box system

The mechanical impedance $Z_m(j\omega)$ represents the load of the mechanical system (e.g. cone, panel) connected to the motor and the influence of the acoustical system (e.g. horn). Fig 3 shows for example an equivalent model of a vented-box loudspeaker system using additional lumped elements

- acoustical compliance C_r of rear enclosure,
- acoustical compliance C_{ab} of vented enclosure,
- acoustical resistance R_{ap} losses in port,
- acoustical mass M_{ap} of the port,
- acoustical resistance R_{al} representing the leakage of the box.

The effective radiation area S_d connects the mechanical with the acoustical domain.

2.2. Measurement Setup

The linear and nonlinear parameters of the loudspeaker model can be identified by measuring only voltage *u(t)* and current *i(t)* at the loudspeaker terminals. There is neither an acoustical, optical nor a mechanical sensor required.

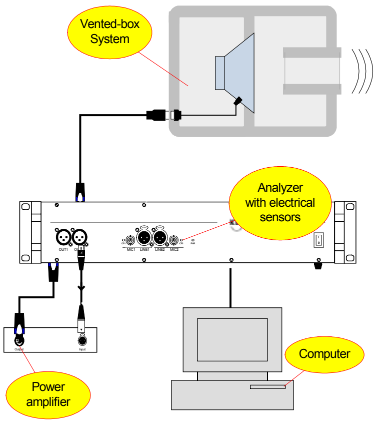

Fig 4: Setup for the measurement of the large signal parameters of a vented-box system by using electrical sensors only.

The electrical measurement can be realized by minimal hardware equipment as illustrated in Fig 4. An analyzer generates a stimulus which is supplied via a power amplifier to the terminals of the loudspeaker. Connecting the speaker with the analyzer via a four-wire cable makes it possible to measure the voltage precisely at the terminals of the loudspeaker independent of the length of the cable. The drive unit may be covered by a grill or mounted in a band-pass enclosure as illustrated in Fig 4 and not accessible to any mechanical or acoustical sensor. The analyzer comprises the electrical current and voltage sensors and AD- and DA-converters to generate the stimulus and to transfer the digital measurement signal to the computer performing further signal processing.

2.3. Stimulus

The stimulus exciting the loudspeaker during testing plays an important role in system identification and should satisfy the following requirements:

- having sufficient bandwidth to identify the resistance and the inductance at low and high frequencies,
- having sufficient resolution to identify the fundamental resonance frequency and the electrical and mechanical damping,
- having sufficient amplitude that the nonlinearities generate sufficient distortion.

A sparse multi-tone is an optimal stimulus and is the basis for a new identification technique. Fig 5 shows the waveform of the sparse multi-tone signal which is a repetitive signal with the period length *T*. Previous to the main measurement a windowed fraction of the stimulus is already supplied to the speaker as a pre-excitation generating steady-state condition. The voltage amplitude spectrum *U(f)* in Fig 6 reveals the fundamental components as distinct lines logarithmically spaced over frequency. The other frequency lines (bins) between the fundamentals show the nonlinear distortion and noise in the voltage signal.

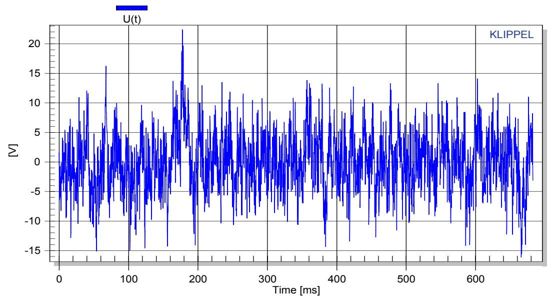

Fig 5: Measured voltage *u(t)* versus time *t* of the stimulus at the loudspeaker terminals by using a multi-tone stimulus

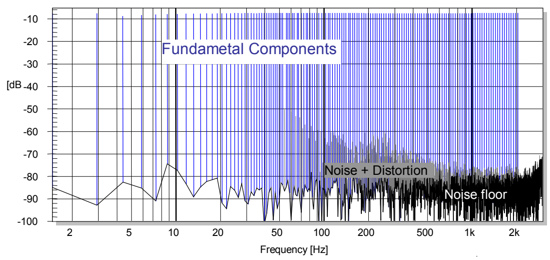

Fig 6: Spectrum *U(f)* of the measured voltage at the loudspeaker terminals by using a multi-tone stimulus

The waveform of the current signal *i(t)* in Fig 7 looks very similar to the voltage signal *u(t)* but the current spectrum in Fig 8 reveals significantly increased level of nonlinear distortion. These distortion components are most valuable symptoms of the loudspeaker nonlinearities and are the basis for the identification of the large signal parameters.

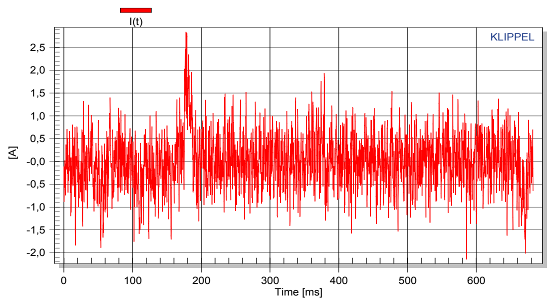

Fig 7: Electrical current *i(t)* measured at the loudspeaker terminals by using a multi-tone stimulus.

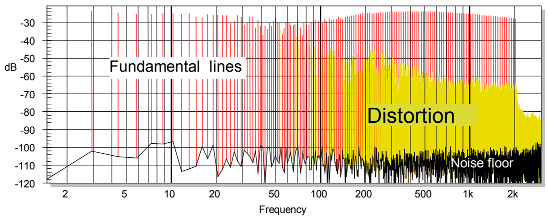

Fig 8: Spectrum *I(f)* of the measured current at the loudspeaker terminals by using a multi-tone stimulus

2.4. Optimal Parameter Estimation

The electrical equivalent models in Fig 2 and Fig 3 give the nonlinear differential equations comprising unknown linear and nonlinear parameters which are to be determined by system identification. Using the voltage signal the current *i'(t)* is predicted by using the differential equation and subtracted from the measured current *i(t)* signal giving an error signal *e(t)=i'(t)-i(t)*. The linear and nonlinear parameters are estimated in an optimal way by minimizing the squared error signal $e(t)^2$ exploiting the properties of the multi-tone signal (patent applied).

2.5. Measurement Time

The length *T* of the stimulus dominates the total measurement time. The post processing of the data is much shorter and can be performed in parallel to the following measurement task (e.g. a sweep for sound pressure measurement). The length of the stimulus *T* determines the number of exciting lines in the sparse multi-tone spectrum and the resolution of the FFT which is synchronous to the stimulus. Persistent excitation of the loudspeaker below resonance frequency f_s and sufficient resolution at low frequencies set a lower limit of the stimulus length *T*.

Speaker Type	Typical Resonance Frequency	Typical stimulus length	Minimal stimulus length
Subwoofer	30 Hz	2.73 s	1,3 s
Woofer	60 Hz	1.3 s	0.68 s
Midrange	300 Hz	0.68 s	0.34 s
Tweeter	2000 Hz	0.17 s	0.17 s
Headphone	100 Hz	0.68 s	0.34 s
Microspeaker	500 Hz	0.34 s	0.17 s
Exciter (shaker)	100 Hz	0.68 s	0.34 s
Closed-box System	60 Hz	1.3 s	0.68 s
Vented-box System	50 Hz	1.3 s	0.68 s

Table 1: Duration *T* of the stimulus required for motor and suspension check of different transducers

Table 1 shows that the stimulus length is inversely related to the resonance frequency f_s. While a microspeaker with a f_s > 500 Hz can be measured by using a 170 ms stimulus a subwoofer with f_s < 30 Hz requires at least a stimulus of *T* = 1.3 s.

3. RESULTS

3.1. Parameters at *x=0*

Although the motor and suspension check should be performed at high amplitudes to assess the nonlinearities of the loudspeaker this measurement also provides the linear parameters at the rest position *x=0*.

3.1.1. Lumped Elements

The following parameters of the lumped elements in the equivalent circuit in Fig 2

- Resonance Frequency f_s,
- Total quality factor Q_{ts} considering all losses,
- Electrical quality factor Q_{es} considering electrical losses only,
- Mechanical quality factor Q_{ms} considering mechanical and electrical losses only,
- Voice coil inductance $L_e(x=0)$, DC-resistance R_e

are identified and describe the properties of the transducer when the coil passes the rest position *x=0*.

If either the force factor *Bl(x=0)* or the moving mass M_{MS} is imported from an external measurement using a perturbation technique (added mass, test enclosure) or a direct laser measurement it is possible to calculate the remaining mechanical parameters in SI units:

- Compliance $C_{ms}(x=0)$ of the suspension in mm/N,

- Stiffness $K_{ms}(x=0)$ of the suspension in N/mm,
- Force factor $Bl(x=0)$ in N/A,
- Moving mass M_{ms} in gram,
- Mechanical resistance R_{ms} in Ns/m.

Due to the visco-elastic behavior of the suspension material (creep) the resonance frequency f_s measured in the large signal domain is usually lower than measured at small amplitudes. Repeating the measurements multiple times will also reduce both the stiffness $K_{ms}(x=0)$ and the resonance frequency f_s. This is a reversible process which can be explained by a temporally change of the fibers in the woven structure of the spider material. This process also occurs in the small signal domain and cause a dependency of the linear Thiele/Small parameters on peak displacement x_{peak}.

Fig 9: Damping material in the port of a vented-box system.

3.1.2. Parameters of vented systems

The MSC can also be applied to drive units mounted in a sealed or vented enclosure while considering the acoustical elements in Fig 3. The measurement provides the

- port resonance frequency f_p considering the acoustical mass of the air in the port and the compliance of the enclosed air,

- quality factor Q_p considering all acoustical losses in the vented system.

The single valued numbers f_p and Q_p are very valuable characteristics for the end-of-line testing of vented loudspeaker systems and give clues for detecting leaks and for finding damping material blocking the exit of the vent within the enclosure as shown in Fig 9.

The MSC can also be used for other mechanical or acoustical systems having an additional resonator (e.g. a flat panel or a horn loudspeaker).

3.1.3. Electrical Impedance $Z_e(j\omega)$ at $x=0$

The electrical impedance response $Z_e(j\omega)$ is usually defined as a linear transfer function between current and voltage at the terminals and is calculated as the ratio of the voltage $U(j\omega)$ and current spectrum $I(j\omega)$ in the frequency domain. This definition is based on linear system theory and requires that the loudspeaker is operated at sufficiently small amplitudes where the nonlinearities inherent in the transducer can be neglected.

If the electrical impedance $Z_e(j\omega)$ is calculated from voltage and current spectra measured at high amplitudes nonlinear distortion corrupts the measurement and produces a distorted shape of the resonance curve. The distortion depends on the properties of the stimulus and has not much value for loudspeaker diagnostics.

However, the nonlinear model in the MSC predicts those distortion and calculates a purified response which corresponds with the electrical impedance $Z_e(j\omega, x=0)$ at the coil's rest position $x=0$.

3.2. State variables

The new MSC technique also identifies all state variables such as displacement x, velocity v, temperature T_v of the coil and the input power P. At high amplitudes the heating of the coil is not negligible and may cause significant increase of the voice coil resistance during measurement.

3.2.1. Peak Displacement

The identification technique also calculates the displacement $x(t)$ versus t as shown in Fig 10 by using the voltage signal $u(t)$ and lumped parameters of the system.

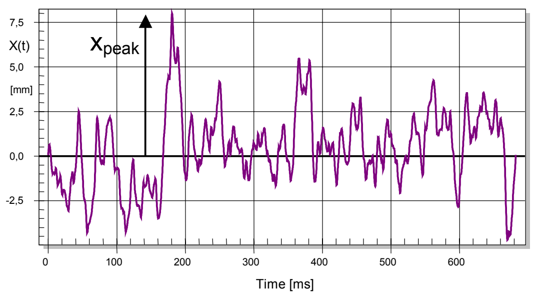

Fig 10: Voice coil displacement $x(t)$ versus t predicted by the large signal model.

The peak displacement x_{peak} derived from the time signal is an important characteristic for end-of-line testing because some loudspeaker defect (e.g. hard bottoming of the voice coil former at the backplate) are initiated by a softer suspension generating a larger peak displacement at low frequencies.

3.3. Large Signal Parameters

The large signal parameters required for quality control are not nonlinear curves but single-valued parameters(coil offset, suspension asymmetry, …) which are easier to interpret and are more convenient in statistical analysis. The single-valued parameters are standardized [4] and can also be derived from the curves describing the nonlinear characteristic in detail.

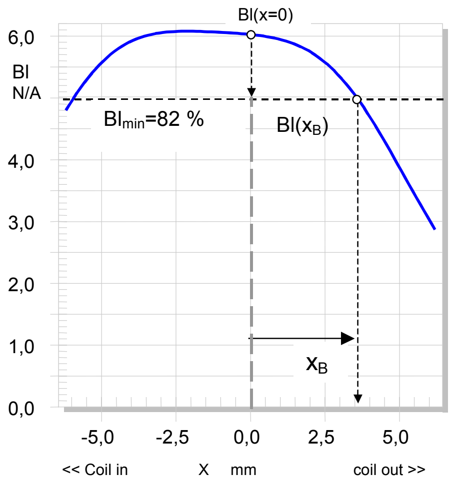

Fig 11: Reading the maximal peak displacement x_B limited by force factor only (*Bl(x)*-curve is measured by conventional LSI technique).

3.3.1. Force factor limited displacement, x_B

The variation of the force factor *Bl(x)* versus displacement *x* generates significant intermodulation distortion in the sound pressure output and limits the maximal mechanical peak displacement X_{max} and the acoustical output. This limit corresponds with a displacement x_B of the coil where the force factor $Bl(x_B)$ decreases to 82% of the value *Bl(x=0)* at the rest position. Fig 11 illustrates the definition of x_B in the *Bl*-curve measured by conventional LSI. If the coil displacement exceeds x_B a two-tone signal comprising a tone at resonance frequency $f_1 = f_s$ and a second tone at $f_2 = 8.5\, f_s$ will produce more than 10 % modulation distortion according to IEC 60268-5.

3.3.2. Voice coil offset x_{offset}

An offset x_{offset} of the voice coil's rest position causes an asymmetrical Bl-characteristic and excessive 2nd–order as well as higher-order distortion components. The offset x_{offset} can be detected by calculating the symmetry point in the force factor curve as illustrated in Fig 12.

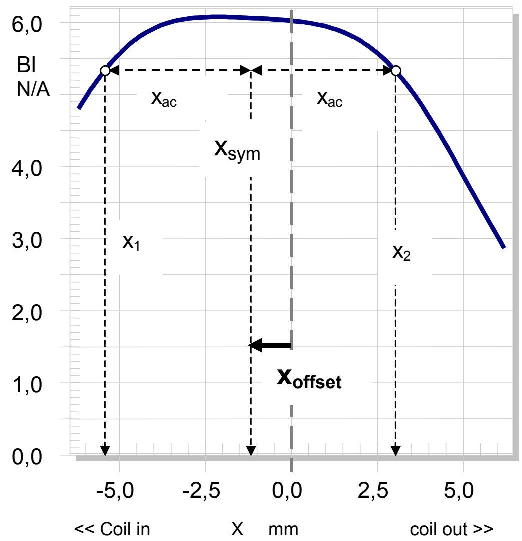

Fig 12: Reading the voice coil offset x_{offset} from the symmetry point in the nonlinear *Bl(x)*-curve measured by LSI.

The symmetry point $x_{sym}(x_{ac})$ is the center point between two points on the *Bl*(x)-curve producing the same *Bl* value

$$Bl(x_{sym}(x_{ac}) - x_{ac}) = Bl(x_{sym}(x_{ac}) + x_{ac}) \qquad (1)$$

as illustrated in Fig 12. The symmetry point x_{sym} is a good estimate of the voice coil offset x_{offset} if the amplitude x_{ac} is high ($x_{ac} > x_{Bl}$) and the two measurement points x_1 and x_2 are at the steep slopes of the *Bl*(x)-curve.

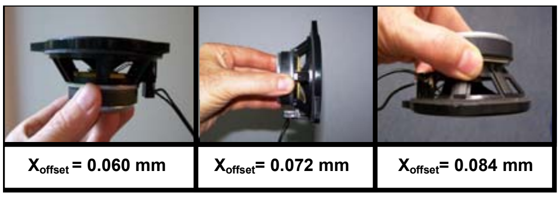

Fig 13: Measurement of the influence of gravity on the voice coil offset x_{offset}.

The MSC determines the voice coil position at high precision. Measurements performed with changed orientation of the drive unit (horizontal, vertical and bottom up) as illustrated in Fig 13 show the influence of the gravity. The weight of the moving parts (coil, suspension, diaphragm) causes a shift of the voice coil position by 12 µm if the loudspeaker is moved from the vertical into the horizontal position. The influence of gravity is negligible in most applications but shows the sensitivity of the MSC.

The voice coil offset can be expressed in absolute units (mm) or referred to the maximal peak displacement x_{peak} and expressed in percent. Changes of the material properties and tolerances in the geometry of the spider, surround and diaphragm are the most common causes for a coil offset in the final product which is not found in the original prototype. An offset of 5 % may already produce excessive distortion in drive units having a small coil overhang or underhang. An ac signal will be rectified and a dc component in the displacement will be generated which increases the offset dynamically and shifts the coil out of the gap. A low voice coil offset and a symmetrical stiffness are basic requirements for the stability of the drive unit.

3.3.3. Compliance limited displacement x_c

The nonlinearity of the suspension also limits the maximal displacement. A sinusoidal excitation tone at the resonance frequency f_s will generate approximately 10 % harmonic distortion if the compliance $C_{ms}(x_c)$ at the peak displacement x_c decrease to 75 % of the value $C_{ms}(x=0)$ found at the rest position $x=0$. This definition of the compliance limited peak displacement is illustrated in Fig 15 showing a $C_{MS}(x)$-curve measured by the conventional LSI technique.

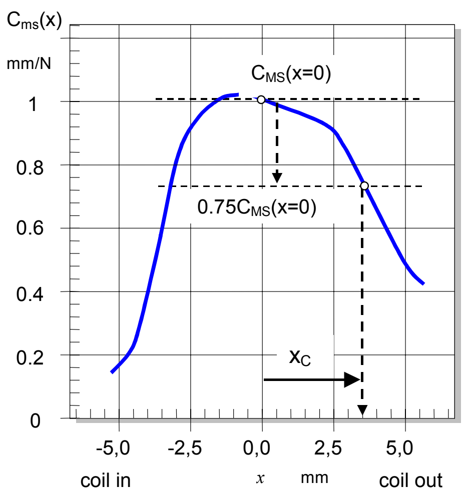

Fig 14: Reading the compliance limited peak displacement x_C in the nonlinear curve $C_{ms}(x)$ measured by *LSI*.

If the compliance limited displacement x_C is smaller than the force factor limited displacement x_B the suspension limits the maximal peak displacement X_{max} and is the dominant cause for the total harmonic distortion at low frequencies ($f < f_s$).

3.3.4. Suspension asymmetry A_K

A symmetrically limiting suspension system may be useful to protect the voice coil former against bottoming and to avoid a hard limiting of the surround, which may damage the speaker and may produce impulsive distortion which are similar to "rub and buzz". If the suspension limits the displacement at one side only or has a strong asymmetry in the $C_{ms}(x)$ characteristic as shown in Fig 15 then this suspension rectifies the ac signal and generates dynamically a dc signal which drives the coil out of the gap. Thus, low-cost suspension parts may degrade the performance of a much more expensive motor structure.

The asymmetry of the *Kms(x)*-curve can be described by the ratio

$$A_K(x_{peak}) = \frac{2\left(K_{MS}(-x_{peak}) - K_{MS}(x_{peak})\right)}{K_{MS}(-x_{peak}) + K_{MS}(x_{peak})} 100\%, \quad (2)$$

using the stiffness at the negative and positive limits $\pm x_{peak}$.

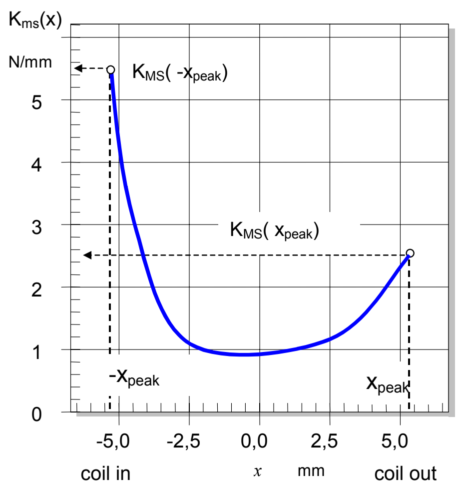

Fig 15: Reading the suspension asymmetry A_K from the nonlinear $K_{ms}(x)$ curve measured by conventional LSI technique.

In well designed and manufactured drive units the absolute value of the suspension asymmetry A_K is less than 20 %. The sign of A_K corresponds with the sign of the dc-displacement generated by an asymmetrical suspension. That means a negative value of A_K causes a negative dc-displacement moving the coil to the backplate (coil in position).

4. VERIFICATION OF THE METHOD

The reliability of the new measurement technique has been investigated on various kinds of drive units (woofer, tweeter, microspeaker, …) as well as complete loudspeaker systems using closed and vented enclosures. The single-valued results (x_c, x_B, A_K, x_{offset}) of the new MSC technique show a very good reproducibility and agree very well with the results of the conventional LSI.

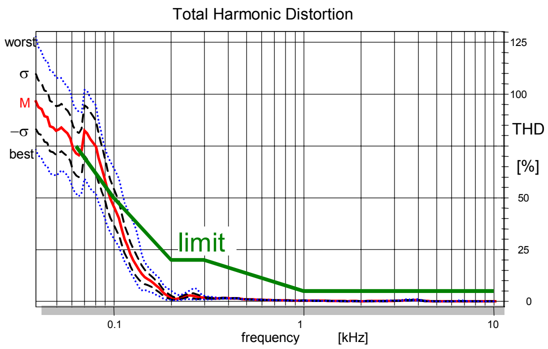

Fig 16: Mean value, standard variation and best and worst curve of the total harmonic distortion measured at 30 headphone drive units.

The evaluation of the new technology will be illustrated on the results found in a systematic investigation performed on a batch of 30 headphone units. First the total harmonic distortion (*THD*) are measured and the mean value M, standard deviation σ and the curves of the best and worst unit are represented in Fig 16. 25 units from the batch failed the end-of-line test because their THD exceeded the allowed limit at resonance frequency. Unfortunately the curve shape of the THD give no further indications about the physical cause of the problem. Comparing the magnitudes of the higher-order components revealed a dominant 2nd-order component which corresponds with an asymmetrical nonlinearity somewhere in the drive unit. Further intermodulation measurements would give further clues about the contribution of the force factor. However, intermodulation measurements should be avoided in QC applications because they are more time consuming than single-tone sweep measurements and more difficult to interpret.

All units of the batch have been measured by the conventional LSI technique and the $K_{ms}(x)$ and $Bl(x)$-nonlinearities of the worst and best unit of the batch are shown as nonlinear curves in Fig 17 and Fig 18, respectively.

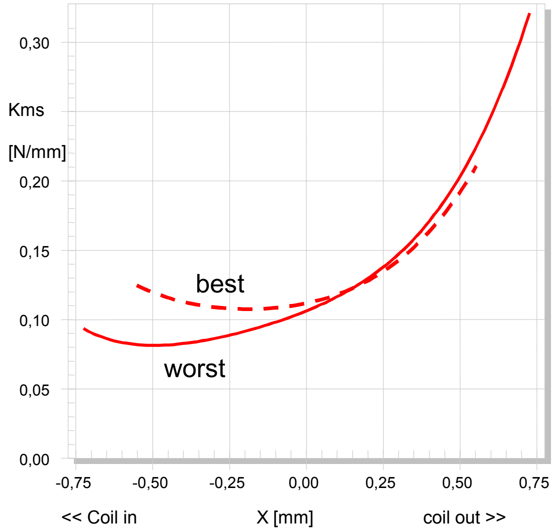

Fig 17: Stiffness characteristic $K_{ms}(x)$ versus displacement x of the best and worst headphone unit measured by the conventional LSI method.

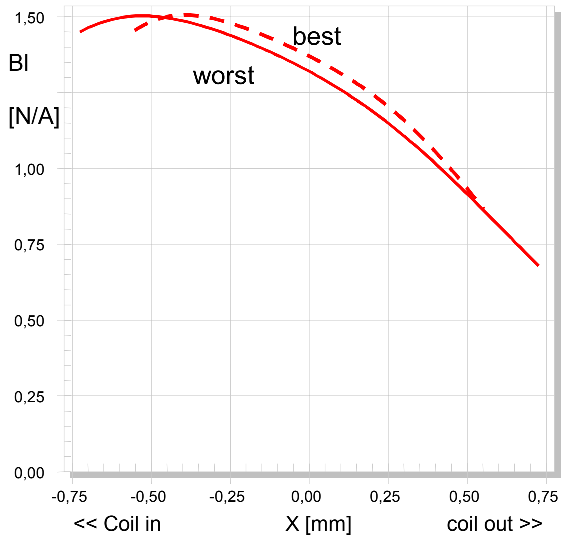

Fig 18: Force factor characteristic *Bl(x)* versus displacement *x* of the best and worst headphone unit measured by the conventional LSI method.

The nonlinear parameters of the 30 units vary significantly due to production tolerances. However, all units have a significant voice coil offset of about 0.5 mm and a distinct asymmetry in the stiffness characteristic. While the LSI requires about 5 minutes for the measurement of each unit the new MSC technique accomplishes this task in less than 1 s.

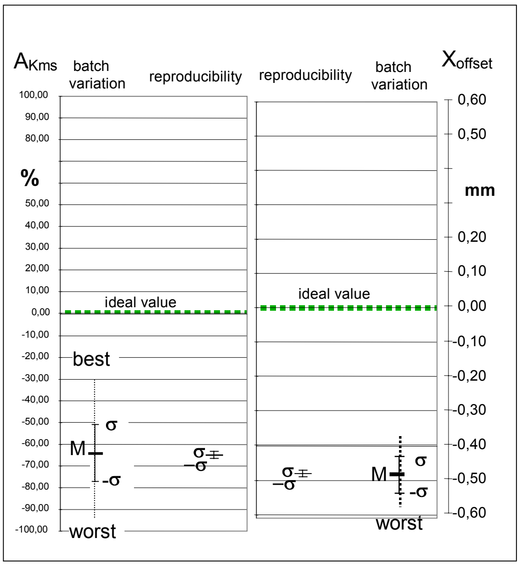

Fig 19: Mean value M, standard deviation σ and the the values of the Stiffness asymmetry A_K and voice coil offset x_{offset} measured by the new MSC method on the complete batch. The reproducibility is tested by repeating 30 times the measurement on one single device.

Fig 19 shows the voice coil offset x_{offset} and the stiffness asymmetry A_K of the best and worst unit, the mean value M, standard variation σ determined by a statistical analysis of all units in the batch. Despite extremely short measurement time the new MSC gives the same results as the time intensive LSI measurement. The standard variation σ of both parameters between the units in the batch is much higher than the standard variation found by repeating the measurement on one unit 30 times.

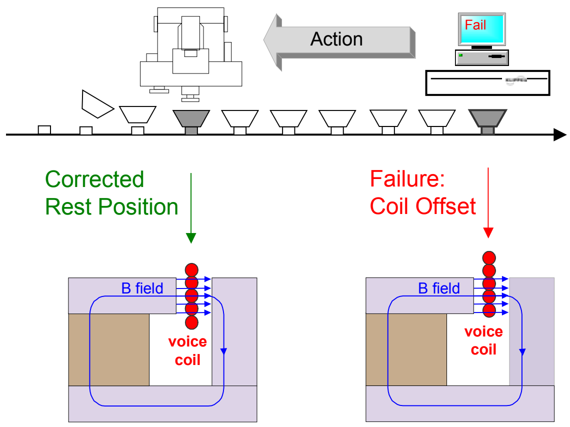

Fig 20: Measurement of the voice coil offset at the end-of-line testing and adjustment of the manufacturing process.

5. CONCLUSION

The new measurement technique for motor and suspension (MSC) opens new ways for end-of-line testing:

- Objective and reliable detection of defects in motor and suspension is possible within the shortest possible measurement time (stimulus length between 0.2 s and 3 s). The high measurement speed of the MSC may be a new starting point for investigating creep and other visco-elastic processes in the loudspeaker which have a low time constant.

- Although the MSC performs measurement at high amplitudes it also provides the lumped parameters and the electrical impedance at the rest position, which correspond with the small signal parameters (T/S).

- The MSC dispenses with measurements of mechanical or acoustical quantities such as displacement or sound pressure. This gives high robustness of the measurement against ambient noise. Using a four-wire connection between the terminals and current and voltage sensors the measurement may also be accomplished over a long distance. Drive units can be measured while being mounted in vented and sealed enclosure.

- Large signal parameters are expressed as single values to support limit setting and statistics (*Cpk, Ppk*) assessing the process stability.

- The interpretation of the large signal parameters is simple and gives detailed indication to understand the physical cause and to find a solution for the problem. For example, a voice coil offset caused by a new batch of suspension parts may be detected as soon as the first unit using suspension parts of this batch passes the end-of-line tester. The MSC provides accurate value of the offset in mm which can be used to correct the coil position at the assembling station as illustrated in Fig 20. While in the past the main concern of end-of-line testing was to separate the defect units from the good ones new measurement techniques like the MSC will provide more diagnostic capability. Using this information as feedback for process control will reduce the rejection rate and increase the yield of the production.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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