Why and How to Test Voice Coil Position in Production Line

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1. Introduction

The large signal behavior of electrodynamic loudspeaker transducers at medium to high excursions is characterized by various nonlinear mechanisms, mainly related to the suspension and the motor. They define the sound quality, stability and peak performance of the final audio system (see **Figure 1**). The nonlinear characteristics of a transducer are already set during the design phase — restrictions are related to price, size, weight, and the target market. The employed materials and geometry of motor and suspension mainly define the overall large signal performance.

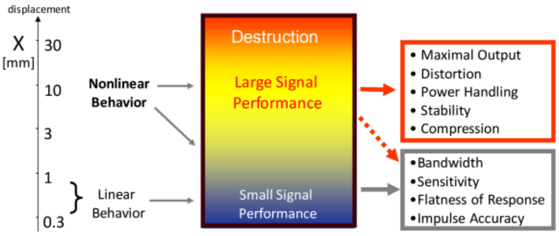

Figure 1: Schematic overview of the operation range of the electrodynamic transducer between small signal performance and overload depending on peak displacement.

These physical limitations make the transducer the weakest part in the audio system, while the suspension is the weakest part of the transducer. Although many nonlinear characteristics can be considered stable in manufacturing because components such as the magnet and pole plates have a fixed geometry, variation in the moving parts may cause a bias or even alter the characteristics.

The soft parts are subject to significant variation that must be considered during assembly in order to ensure optimal voice coil position and to prevent suspension asymmetries as well as bias in the interaction of spider and surround. A simple voice coil offset from its ideal position can dramatically degrade the overall performance of the audio system, especially for highly efficient transducers with very nonlinear motors.

In consequence, a production test system must not only ensure that the product is free from severe defects but also that it fulfills the specified performance related to audio quality, stability, maximal excursion, and output. Most test systems mainly rely on testing the nonlinear (harmonic) distortion in the acoustical output of the device under test (DUT). However, such well-established methods are not always critical enough, barely provide root cause information, and may even be misleading in some cases. Optimal coil position for maximal symmetrical peak excursion cannot be ensured by plain distortion tests, especially for microspeakers and headphone transducers.

The goal is detecting systematic motor and suspension problems as early as possible for immediate root cause analysis and effective process control to ensure consistent product quality, dealing with varying quality of the soft parts.

2. Effects of Uncontrolled Voice Coil Position

In electrodynamic transducers, the nonlinear force factor Bl(x) is considered the main root cause of distortion and stability problems at high excursions together with the nonlinear suspension stiffness Kms(x).

Figure 2 illustrates an example for the nonlinear force factor depending on the displacement of the voice coil relative to its rest position (at x = 0 mm). The voice coil is centered in the magnetic field, resulting in an almost symmetrical characteristic with its sensitivity maximum close to zero displacement. Any displacement introduced by an audio signal with low-frequency content applied to the voice coil can instantaneously and continuously alter the effective force factor. Compression and nonlinear signal distortion (i.e., harmonic distortion and intermodulation distortion) in the sound pressure output are the consequences, as shown in **Figure 3**.

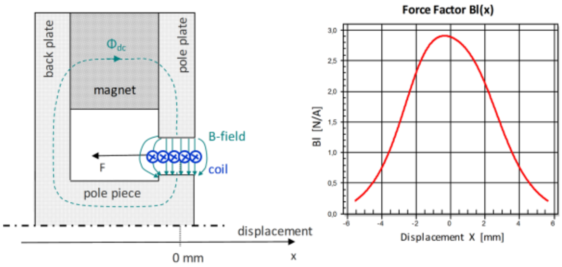

Figure 2: Here is the cross section of an electrodynamic transducer motor and the corresponding nonlinear force factor Bl(x).

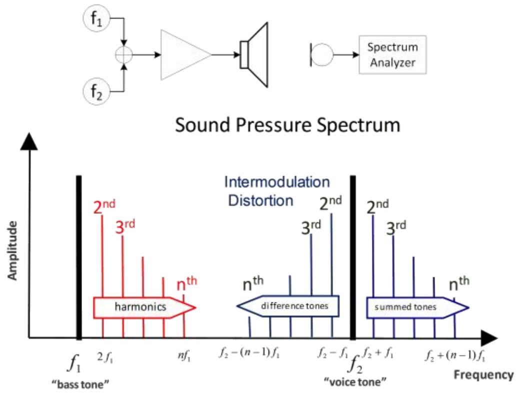

Figure 3: Sound pressure output of two-tone signal played through a loudspeaker at high excursion.

If the voice coil rest position is altered from its optimal position, the Bl(x) characteristic is shifted on the displacement axis and an additional asymmetry with respect to the rest position is introduced, resulting in mainly second (even) order harmonic distortion (HD) of up to 5% of the total signal. A much more critical effect of Bl(x) is broadband intermodulation distortion (IMD) that can easily reach amounts of 20% to 40% when a bass tone and a voice tone are played simultaneously with high amplitude, especially when the coil rest position is located on the steep slopes of the Bl(x) curve. As a consequence, the sound quality is significantly impaired compared to a driver with a well-centered coil. Consequently, distortion measurements seem to be a useful strategy in order to detect a voice coil offset by its symptoms.

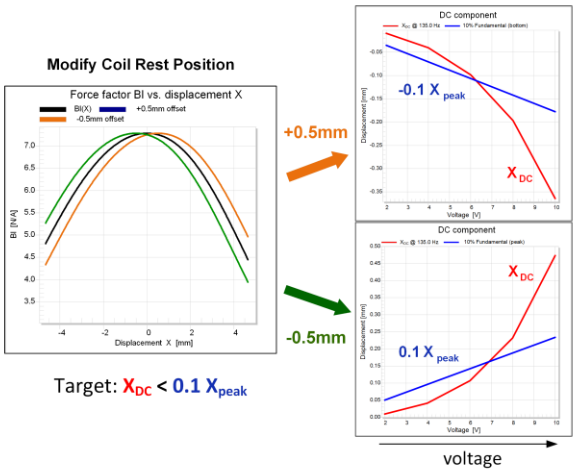

Figure 4: This illustration shows the Simulated effect of a positive and negative voice coil offset on the generated dynamic DC displacement. At high input voltages, the displacement DC component exceeds 10% of the AC peak value. The direction of the generated DC corresponds to the direction of coil offset - the coil is shifted even further away from the optimal rest position.

Another effect of the nonlinear force factor is dynamic DC displacement, a very important factor for the stability of the transducer. The major causes are motor asymmetries (e.g., as a consequence of non-optimal coil position). The example shown in **Figure 4** illustrates how a positive and negative coil shift affects the direction and amount of dynamically generated DC displacement, depending on input voltage of a critical signal. If the audio signal contains frequencies between the driver's resonance fs and 2 × fs, the center point of the AC coil movement may be shifted significantly away from the rest position. In bad cases, the amount of DC displacement generated may have the same magnitude as the AC amplitude. It is directly corresponding to the amount of asymmetry of the force factor defined by the coil rest position or field asymmetry.

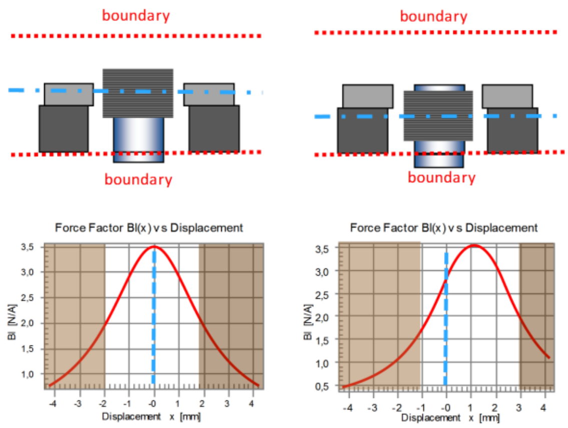

Figure 5: Influence of a non-optimal coil position on the usable negative and positive peak displacement is limited by geometrical boundaries.

Distortion and stability problems may not always be critical for linearly designed motors. Still, the voice coil position matters in terms of displacement limiting, defined by geometrical boundaries as depicted in **Figure 5**. Microspeakers especially do not have a self-limiting suspension, for the most part, and most signal limiter algorithms assume a certain symmetrical excursion range. The safety margins related to coil position variation in manufacturing need to be relatively high because mechanical limiting must be avoided under all conditions to prevent destruction or impulsive distortion. The consequence is less available AC peak displacement and eventually less output.

3. Drawbacks of Traditional Distortion Test Methods

Since the nonlinear force factor and its asymmetry related to coil position is one of the main causes of signal distortion in the sound pressure output, HD and IMD measurements are a straight-forward approach for evaluation— commonly used in both R&D and end-of-line (EOL) testing. The basic assumption is that any offset from the optimum coil rest position increases output signal distortion levels that can be simply measured with a microphone and an audio analyzer. Limits may be applied to the distortions levels in order to distinguish good from bad devices.

This assumption is mostly true for IMD, which is the main effect of the nonlinear force factor and can be effectively measured using two-tone signals (bass or voice tone sweep). This approach is a useful tool in R&D, but due to the limited test time and poor use for measuring other characteristics, it is usually not applied in EOL testing.

Multi-tone stimuli are an alternative choice to get a broad-band distortion fingerprint of the tested device. All mechanisms that create distortion are activated, but the diagnostic value is very limited. However, multi-tone signals are useful for nonlinear parameter measurement, which is addressed in the next section.

Pure harmonic distortion measurements can be realized in a more efficient way using sinusoidal signals with varying frequency, such as stepped sine signals or continuous sweeps (chirps). Such stimuli—especially the chirp—is more suitable for EOL testing since meaningful measurements can be performed in very short time. In addition, common characteristics such as frequency response, polarity, impulsive distortion (e.g., rub & buzz or loose particles), and impedance may be measured simultaneously. Also, single harmonics or total harmonic distortion (THD) can be obtained. Second-order distortion is a useful indicator for asymmetries in the nonlinear characteristics, such as Bl(x) asymmetry caused by coil offset.

However, HD is not a unique characteristic of the motor, as shown in **Figure 6**. In many cases the nonlinear stiffness of the suspension is the main cause of harmonics below the driver's resonance frequency. Therefore, the distortion test only reflects a mix of various and partly independent root causes. If both the suspension and the motor have asymmetrical characteristics, a coil offset may even reduce distortion, as depicted in the example in **Figure 7**. The transducer may pass the harmonic distortion test, although the displacement clearance and stability is significantly reduced.

Even in those cases where the THD or the second-order harmonic distortion measurement indicate that the DUT has a different nonlinear behavior than the golden reference device, it still lacks some basic diagnostic information:

- What was the root cause of the failed test and how to fix it?
- Was it a problem of the suspension part, the voice coil, or the assembly?
- If it was related to coil position and the problem is systematic, by how much and in which direction must the position be adjusted (in millimetres)?

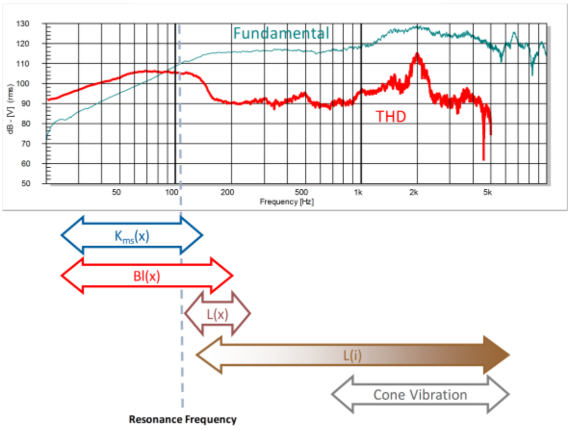

Figure 6: These are some of the major causes of harmonic distortion in sound pressure output of electrodynamic transducers over frequency.

In order to answer these questions using traditional test methods, the failed units must be evaluated by experts in a diagnostics station or even in the R&D lab. This is very time-consuming and often not practical. In the meantime, the yield rate may drop, significantly reducing profit.

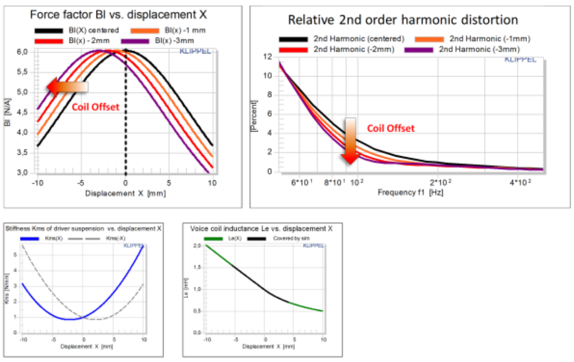

Figure 7: Simulated second order HD vs. coil offset—the distortion is reduced with increasing offset due to asymmetric suspension stiffness.

4. Testing Voice Coil Position Based on Nonlinear Parameter Measurement

Since pure output distortion tests have various drawbacks, it is desirable to measure the voice coil position directly. Mechanical sensors are mostly not applicable to an assembled transducer and they are hardly suitable to evaluate the optimal positioning of the voice coil with respect to the magnetic field.

As previously stated, the voice coil rest position reflects in the nonlinear force factor Bl(x). Therefore, measuring this nonlinear transducer parameter is suggested as a superior approach to pure output-based distortion testing. Since the linear transducer model, based on Thiele- Small (T-S) parameters, is only valid at very small excursions, a nonlinear transducer model is required for this purpose. Such parameter-based models have been developed and successfully applied in transducer design, diagnostics and control. In R&D and prototype evaluation, nonlinear transducer parameter measurements are a common tool in the loudspeaker industry.

Due to the coupling of electro-mechanics, the speaker itself can be used as a sensor to identify the linear and nonlinear parameters by exploiting the terminal voltage and input current measured at high amplitudes (see **Figure 8**). For absolute calibration of the mechanical parameters, an optional laser displacement sensor may be used or a previously measured (typical) moving mass or Bl(0) can be imported.

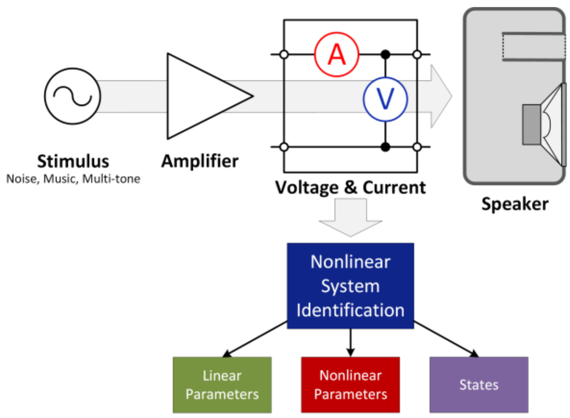

Figure 8: Measurement of transducer nonlinear parameters is based on measurement of terminal voltage and input current.

Virtually any broadband audio signal stimulus may be used for nonlinear parameter identification, but for high-speed testing in the production line, a multi-tone complex is the optimal test signal in order to excite nonlinearities efficiently and separate resulting distortion easily while keeping the test as short as possible. **Figure 9** shows an example frequency spectrum of the transducer input current. The distortion generated by the transducer nonlinearities are shown between the sparse, excited frequency lines in the signal spectrum.

The nonlinear parameters, such as Bl(x) or Kms(x) are identified by fitting the transducer model to the measured data. In R&D, those parameters have a high diagnostic value, but they are not suitable for EOL testing. Single value parameters like voice coil offset in millimeters or stiffness asymmetry in percent are more suitable for limit setting and process control.

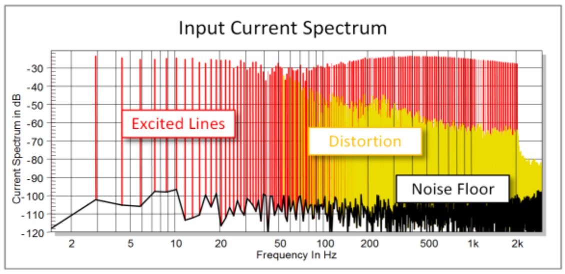

Figure 9: The multi-tone input current spectrum of a transducer is operated at high amplitudes.

In order to determine the coil offset based from the Bl(x) curve, two methods are suggested as shown in **Figure 10**: the Bl(x) symmetry point and the coil offset relative to a reference DUT. The symmetry point according to The International Electrotechnical Commission (IEC) standard 62458 is a universal tool to evaluate any kind of asymmetry in the curve. Starting at the curve maximum, it equals the center point value on the X-axis between two points having the same Bl value. Thus, the value depends on amplitude and may be different at low and high excursions. For motors with symmetric motor topology, the symmetry point is relatively constant over amplitude and indicates the coil position directly (with negative sign), which ideally should be close to zero.

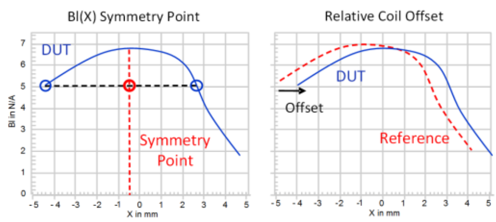

Figure 10: These methods for measuring voice coil position are based on nonlinear force factor Bl(x).

For transducers with inherent asymmetry in the magnetic field or linear motor designs with overhung coil as shown in the example in **Figure 11**, the symmetry point can be misleading. In order to estimate the coil position, it should only be read at maximum amplitude where the main Bl(x) slopes are dominant. A symmetry point equal to zero is not always desirable for optimal performance at small or medium amplitudes. For some motor topologies, this method is too ambiguous or not applicable at all.

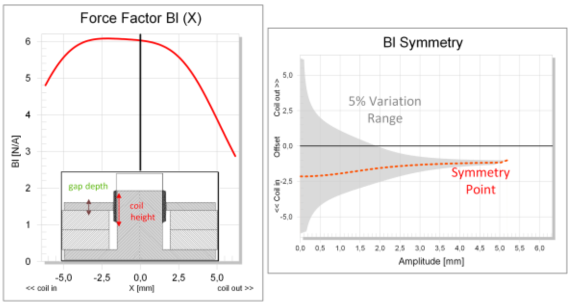

Figure 11: This graph shows the Bl symmetry point for a transducer with overhung coil design.

In such cases, a preferable method is based on comparing the Bl(x) characteristic to a known reference DUT of the same type (e.g., a “Golden” DUT). Based on the assumption that the inherent curve shape is mainly defined by the motor geometry and thus stable, the offset is determined by estimating only the curve shift. This approach is the most universal method, but always requires an approved reference unit that defines the optimal or desired coil position.

For a typical automotive woofer, the additional test time for the nonlinear parameter test is between 1 s and 2 s. An additional small signal impedance test may be omitted, because effective linear T-S parameters can be determined at high amplitudes as well. Additional pre-excitation signals for transducer break-in can also be skipped and replaced by the high-level nonlinear test. Using high-speed chirp signals for additional acoustical tests, the overall test time can be optimized to be 2 s to 3 s while gaining much better diagnostic information for process control.

5. Conclusions

Ensuring an optimal voice coil rest position is essential for the audio quality, stability, and displacement clearance of loudspeaker transducers, especially for small or highly efficient ones. The coil position varies significantly in manufacturing due to systematic variation of the soft parts and moving parts assembly. Modern EOL test systems should be able to directly or indirectly test large signal characteristics to ensure desired target product quality and to guarantee specified peak performance. Traditional harmonic distortion tests can be a simple approach to check motor and suspension problems qualitatively, but results can be very ambiguous or even misleading and have low diagnostic value.

Directly testing the voice coil position by nonlinear parameter measurement is a superior method to identify the root cause of distortion, instability, and peak displacement limitation with high accuracy. Quantitative information is provided that can be used for immediate process control in order to fix systematic problems as early as possible. The diagnostic value saves time and money by reducing manual analysis effort and increasing yield rate through early defect detection. This balances the additional test time spent while the overall time is kept low, using efficient stimuli and test sequences.

Since the soft parts are the most critical and variable component of the loudspeaker, a critical EOL test for controlled manufacturing is required. However, optimal performance over the product’s lifetime can only be ensured using adaptive, nonlinear speaker control to overcome production variance, aging, and environmental influence in the final application.

The presented approach is not only applicable to electrodynamic loudspeakers, but with modification also to other transducer types (e.g., balance armature drivers) in order to test the armature offset within very short time for optimal and reproducible audio quality.