Fast and Sensitive End-of-Line Testing

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Measurement time is a crucial factor for the total cost and feasibility of end-of-line quality control. This paper discusses new strategies minimizing the test time for transducers and audio systems while ensuring high sensitivity of defect detection, extracting comprehensive diagnostics information and using available resources in the best possible way. Modern production lines are fully automated and benefit highly from high speed testing. Optimal test stimuli and sophisticated processing in combination with multi-channel test design are the key factors for smart testing. Appropriate acoustical, mechanical and electrical sensors are discussed and suggested. Furthermore, parallel or alternating test schemes reduce the overall test time. Finally, typical concerns and pitfalls when testing at high speed are addressed and illustrated by measurement results.

1 Introduction

The primary goal in end-of-line (EOL) testing is to reliably separate good and bad devices under test (DUT) and to minimize false positive or false negative test verdicts. However, some defects generate only minor symptoms which are not audible for the untrained ear but become worse during product life and should not be shipped to customers. Human operator's judging based on listening is very sensitive for indications of a potential defect and use the sinusoidal generator effectively to minimize the test time. An automatic test system replacing the stressful human work can improve the reproducibility, repeatability and comparability of the test results and provide superior sensitivity and reliability in the PASS/FAIL classification while reducing the test time significantly.

Considering manufacturing conditions, this paper investigates the physical constraints limiting sensitivity and speed of automatic testing and searches for optimal solutions that can be realized with minimal effort.

2 Particularities of EOL Testing

Typical measurements performed during product development are usually not time restricted and are applied to selected samples only. A high signal-to-noise ratio (SNR) can be achieved by averaging the monitored signals (noise suppression) and by using a standardized test setup such as an IEC baffle placed in a silent, anechoic and climatized environment. Testing at the end of the manufacturing process requires the following compromises to make the testing of all DUT (100% testing) feasible:

- Low SNR (short test time, no averaging)
- Non-steady state excitation condition
- Properties of DUT may change over time (glue not completely dried, higher temperature from drying process, break in effects, …)
- Measuring small signal characteristics (transfer function, electrical impedance, T/S parameters) at larger amplitudes
- Test conditions (box, microphone position) are not identical at all EOL test stations.

Effort has to be applied to suppress undefined conditions and influences that limit the reproducibility of the results such as

- Clamping and positioning of DUT and sensors
- Handling by human operator
- Acoustic load changes (box leakage)
- Connection problems
- Verdict corruption by external acoustic or mechanical disturbances
- Significant temperature / humidity variation.

Repeatability and reproducibility of test results shall be checked with standardized methods such as a gauge R&R test [1]. Repeatability is defined as the consistency of the results by retesting a DUT with the same instrument under identical measurement condition. Reproducibility studies check the consistency of the results when different operator perform the measurement.

Modern measurement devices using sufficiently good sensors cause a much smaller variance than electroacoustical devices under test due to time varying properties (e.g. visco-elasticity of the suspension, self-heating) and random properties of the defects (e.g. loose particles).

For EOL testing, reproducibility is more important than the comparability with standard measurements during the R&D process.

3 Optimum Stimulus

The choice of the test stimulus signal is crucial for designing time efficient EOL tests. A single-tone stimulus signal with varying frequency is the most popular stimulus in manufacturing. The major reason for using sinusoidal test signals is that the energy of the stimulus is applied to a narrow frequency band. Thus, it provides the best excitation of

a) regular resonators and nonlinearities accepted during the design phase and
b) irregular nonlinear dynamics caused by mechanical and acoustical defects during production.

A single tone sinusoidal excitation also simplifies the separation of harmonic and noise components.

More complex test stimuli such as two-tone or multi-tones, pink noise, or even speech and music are crucial for evaluating the reproduced sound quality during product development. At least two tones are required to activate some nonlinearities (Doppler, inductance L(x)) and to generate intermodulation distortion.

3.1 Steady State Measurements

The linear behavior of the DUT can be measured with any stimulus providing sufficient excitation in the band of interest to achieve a reasonable SNR. This can be achieved by steady-state measurements: The acquisition begins when the transient phase is settled and the amplitudes of all state variables (e.g. pressure, excursion, current) are constant. The transient phase depends on the resonance frequency f_n and quality factor Q_n of the fundamental and other higher-order modal resonators (cone break up modes). Those resonators generate poles in the overall transfer functions and a transient when the stimulus is changed. The envelope of this transient decays with an exponential function proportional to $e^{-t/\tau}$ with the time constant [13]:

$$\tau = \frac{Q_n}{\pi f_n} \qquad (1)$$

In the context of EOL testing, a small deviation between the measured amplitude during the transient phase and the ideal steady-state value is traded in for measurement time. For example, an error of 4% in the measured amplitude requires a pre-excitation time

$$t_{s,4\%} = Q_n / f_n \qquad (2)$$

before the data acquisition starts. Doubling the pre-excitation time would reduce the error to 0.2%.

For example, a subwoofer operated in a sealed enclosure generating a quality factor Q_0=1 and resonance frequency f_0 = 50 Hz must be excited for 40 ms until an amplitude accuracy of 0.2% is reached. In a vented enclosure, the higher quality factor Q_p=10 of the port resonance of 50 Hz would increase the pre-excitation time to 400 ms.

3.2 Stepped Sine Stimulus

The stepped sine stimulus comprises multiple sections i with $i \geq 1$ where each step has the duration

$$t_i = P_i T_i = \frac{P_i}{f_i} \qquad i \in \mathbb{N} \,|\, i \geq 1 \qquad (3)$$

determined by the integer number P_i of full sine oscillations with period length T_i and excitation frequency

$$f_i \approx f_{i-1} 2^D \qquad i \in \mathbb{N} \,|\, i \geq 1 \qquad (4)$$

which are selected with a constant spacing D on a logarithmic frequency scale. The exponent D is inversely proportional to the number of excitation frequencies per octave (number of steps = $1/D$).

Defining a maximum quality factor Q_{max} which is larger than any quality factor Q_n expected in the regular and irregular modal resonances of the DUT, the relative spacing D between the tone density frequencies can be determined as

$$D = \log_2 \left(1 + 1/Q_{max}\right) \qquad (5)$$

to have at least one measurement point within the 3 dB decay bandwidth of the critical resonator.

The maximum quality factor Q_{max} can be also used to determine the optimal number of periods P_{opt} applied to all steps

$$P_i = P_{opt} = 1 + \left\lfloor \frac{Q_{max}}{8} \right\rfloor \qquad i \in \mathbb{N} \,|\, i \geq 1 \qquad (6)$$

ensuring that the resonator stores during the transient excitation half of the energy of steady-state condition. Theoretically, a single period P_i=1 in all sections would be sufficient if the spacing D between the frequencies is much smaller than the bandwidth of the modal resonator in the device under test and the multiple steps are exciting one resonator. In practice, the minimum number of periods is set to a larger value ($1<P_i<5$) that simplifies the analysis of the measured state signals. The minimum number of excited frequencies in one octave defined by spacing D in Eq. (5) is the most critical requirement for exciting the resonators by stepped sine stimuli in EOL tests. This problem will be illustrated on practical examples in section 3.4.

The optimum length of the total stimulus can be calculated and approximated for N/D as

$$T_s = \sum_{i=1}^{N/D} \frac{P_{opt}}{f_0 2^{Di}} \approx \frac{P_{opt}}{f_0} \frac{1}{\left(1 - 2^{-D}\right)} \qquad (7)$$

using the number N of octaves covered by the sweep

$$N = \log_2 \left(\frac{f_e}{f_0} \right) \qquad (8)$$

between the start frequency f_0 and end frequency f_e. Assuming a maximum quality factor Q_{max} =16 requires a total number of 80 steps and 3 periods for each step. The total stimulus length is about 2.5 s covering 10 octaves above f_0=20 Hz.

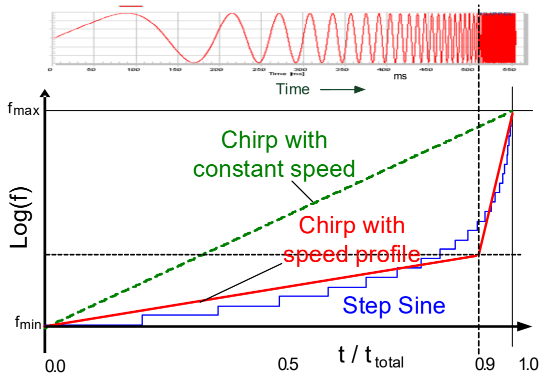

Figure 1: Time-frequency mapping of a stepped sine sweep, a chirp with fixed logarithmic sweep speed and a composed chirp with two different sweep speeds.

3.3 Logarithmic Chirp

A continuous sinusoidal chirp is defined as a sine-based signal with continuously changing frequency

$$f(t) = f_0 2^{\beta t} \qquad 0 \le t \le T_s \tag{9}$$

over the measurement time T_s using a constant sweep speed

$$\beta = \frac{N}{T_s} = \frac{1}{T_s}\log_2\left(\frac{f_e}{f_0}\right) \tag{10}$$

between the start and end frequency. Figure 1 compares a chirp signal with constant sweep speed β=const. shown as dashed line with the stepped sine wave shown as a staircase line within the same total measurement time T_s. The slope of the chirp in the frequency-time mapping at low frequencies is greater than for the stepped sine but it is smaller at higher frequencies. Therefore, the optimal sweep speed

$$\beta_{opt} = \log_2\left(1+1/Q_{\max}\right) f_0 \tag{11}$$

is limited by the maximum quality factor $Q_{\max}$ at the lowest frequency f_0. This slow sweep speed is not required at high frequencies and increases the total measurement time T_s unnecessarily.

In practice, a higher sweep speed $\beta > \beta_{opt}$ can be used if the shorter stay of the sinusoidal excitation signal within the 3 dB bandwidth of the low frequency resonator is compensated by a larger amplitude of the stimulus at those frequencies (applying amplitude shaping to those frequencies).

The fundamental resonance f_0 of the transducer's piston mode has usually a low total Q_{TS} and the settling time is relatively short. Critical are the natural frequencies of the rocking modes [14] which are usually above the fundamental resonance but have a very high quality factor $Q_{1/2} > 20$. Here, an increase of the amplitude by 3 dB may compensate for doubling the sweep speed β reducing the total measurement time by factor 2.

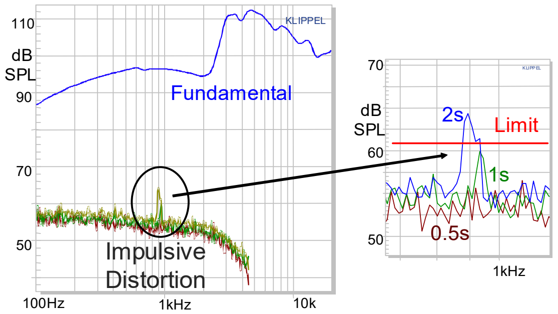

Figure 2: Impulsive distortion generated by a parasitic resonator (defect) with high Q-factor in a headphone measured with a logarithmic chirp of different length (0.5 s, 1 s and 2 s)

The relationship between sweep speed and amplitude of the resonator response is illustrated with a defect generated in a headphone shown in Figure 2. A loose part generates parasitic vibration at 900 Hz with a high quality factor of Q>20. Using a logarithmic chirp with 2 s length from 100 Hz to 20 kHz, the critical vibration of the resonator can be excited and detected as impulsive distortion in the measured sound pressure signal. Doubling the sweep speed and shorting the stimulus to 1 s reduced the symptom by about 4 dB. For extremely short measurement time of 0.5s the symptom was covered by measurement noise. An increase of the amplitude of the stimulus in this frequency band can partly compensate for the reduced energy provided by the faster sweep speed.

3.3.1 Variable Sweep Speed

For electro-acoustical devices, the ideal sinusoidal stimulus is a combination of the dense excitation inherent in the chirp and using the frequency time mapping of the stepped sine stimulus shown in Figure 1. Thus, the sweep speed β shall not be a constant but shall rise to higher frequencies. This yields a chirp with a constant number of periods per decade as also illustrated in Figure 1. Such a chirp can be defined as a sine-based signal with continuously changing frequency

$$f(t) = f_0 2^{\beta(t)t} \qquad 0 \le t \le T_s \tag{12}$$

where the sweep speed itself depends on the instantaneous frequency and the expected maximum quality factor $Q_{\max}$ of the resonances.

$$\beta(t) = \log_2\left(1+1/Q_{\max}\right) f(t) \tag{13}$$

However, this stimulus does not allow a simple separation of the harmonics in the time domain as proposed by Farina [17]. It is more useful to approximate the frequency time mapping of the stepped sine by a chirp comprising multiple sections with different but constant values of the sweep speed.

$$\beta(t)=\beta_i \approx \log_2\left(1+1/Q_{\max}\right) f(t_i) \qquad (14)$$
$$\text{with} \quad t_i \le t < t_{i+1}$$

In practice only two sections are required to get a sufficient approximation, shown as a thick solid line in Figure 1. For a full audio band chirp (20 Hz to 20 kHz) where the sweep speed above 1 kHz is five times higher than at lower frequencies the total test time is reduced to 53% of a traditional chirp with constant sweep speed.

3.4 Chirp Contra Stepped Sine

The selection of an optimal stimulus and the proper adjustment to the particular DUT shall be illustrated with a woofer prone to rocking modes generating impulsive distortion at high amplitudes due to voice coil rubbing. The rocking mode analysis reveals two modal resonances at about 200 Hz with a high quality factor Q ≈ 25.

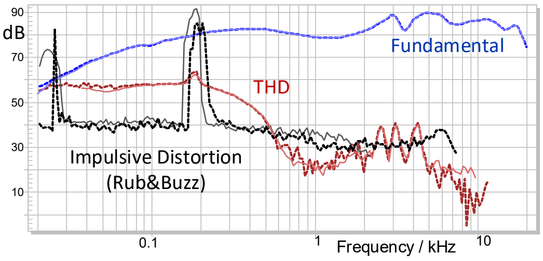

Figure 3: Frequency responses of SPL fundamental, THD and impulsive distortion ID measured with a continuous logarithmic chirp with T_s= 0.6 s shown as solid line and with stepped sine sweep T_s= 4.4s (dashed line)

A stepped sine stimulus with 20 tones per octave fulfilling the requirements that at least one tone is present in the narrow 3dB bandwidth and that it has the optimal period number P_{opt}=3 requires a stimulus length T_s=4.4s to cover the audio band 20 Hz – 20 kHz. A chirp using a sweep speed profile with a much shorter duration T_s=0.6 s is also used as a stimulus for the same DUT.

Figure 3 reveals that both stimuli provide similar frequency responses of the SPL fundamental, total harmonic distortion (THD) and impulsive distortion (ID) which is a sensitive symptom for voice coil rubbing and other defects [2].

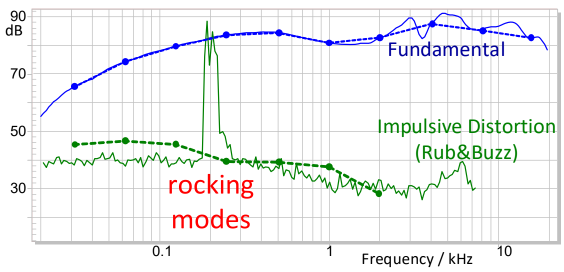

Figure 4: Frequency response of SPL fundamental component and impulsive distortion ID(*f*) measured with a stepped sine stimulus (dashed line) and continuous log chirp with speed profile (solid line) using the same total stimulus length T_s=200ms.

Figure 4 shows the result of a modified measurement where both, the stepped sine and the chirp stimulus have the same total length T_s=200 ms. While the chirp signal excites all frequencies and provides symptoms of voice coil rubbing in the impulsive distortion ID at high resolution, the stepped sine stimulus (P_{opt}=3) can only place excitation tones at 1 octave distance and is unable to excite the rocking modes sufficiently to generate a distinct symptom of the defect. Furthermore, the low number of excitation tones shown as dots in the curves also severely limits the resolution of the frequency responses.

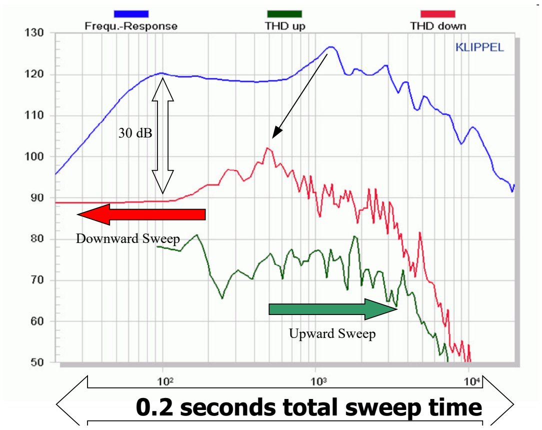

Figure 5: Errors caused in the harmonic distortion of DUT with modal resonances using a chirp sweeping downwards in 200ms

3.5 Sweep Direction

The direction of the sinusoidal sweep is crucial in fast EOL tests where the ringing of modal resonances generate artifacts in the harmonic distortion measurements. For example, **Fehler! Verweisquelle konnte nicht gefunden werden.** shows that sweeping downwards within 200 ms generates 12dB more distortion at 500 Hz than sweeping upwards. Sweeping upwards generates the correct THD values that correspond to the results measured with steady state and chirps with a slower sweep speed. Sweeping downwards the modal resonators will be excited and the post ringing generated by high quality factors will be interpreted as 2^{nd}, 3^{rd} and higher-order distortion. The modal resonance at 1kHz corresponds with the THD maximum at 500 Hz where the ringing of the fundamental component contributes to the 2^{nd}-order harmonic. A chirp with rising frequency generates the harmonic components before the excitation frequency arrives at those frequencies. The accurate measurement of the harmonic distortion measurement can be completed before the ringing at the modal resonance frequencies begins.

Another benefit of upwards sweeps is that initial low frequencies help to break-in the transducer when operated for the very first time after production. An additional low frequency / high displacement signal can be also used, not only for breaking-in the transducer but also for decreasing the settling time of the low start frequency.

3.6 Multi-tone Complex

The sinusoidal chirp with frequency dependent amplitude shaping and sweep speed profile is a powerful stimulus for EOL testing but this stimulus can not generate nonlinear interaction between multiple spectral components. A multi-tone complex representing the spectrum of a typical audio signal generates deterministic intermodulation distortion and random components which can be easily separated at the non-excited frequency bands in the sparse excitation spectrum. The intermodulation distortion is required to identify the regular nonlinearities inherent in the speaker [16]. Some irregular loudspeaker defects such as voice coil rubbing need a broadband stimulus to produce high values of excursion and acceleration at the same time to generate symptoms that are audible or at least detectable by a measurement instrument.

4 Sensors and State Measurement

A microphone measures the sound pressure in the near field of the DUT to provide

- SPL of fundamental and other distortion components in the near field of the transducer
- Air leakage symptoms from glue problems and small holes in enclosures, port noise
- Indications for production noise disturbances (air-born noise)

Electrical sensors measuring terminal voltage and input current are used to :

- Identify impulsive distortion indicating connection problems
- Ensure proper excitation signal and power amplifier operation (voltage at terminals)
- Obtain linear electrical parameters (Thiele/Small)
- Obtain non-linear transducer parameters (stiffness asymmetry, offset in voice coil rest position and distance to boundaries)

If the radiating surface of the DUT is accessible for an optical laser sensor, the voice coil displacement can be measured to determine

- Absolute values of Bl, M_{ms}, K_{ms} and other mechanical lumped parameters
- Peak and bottom displacement
- Defect location by mapping impulsive distortion versus displacement

An accelerometer can be used to measure:

- Shakers and other mechanical actuators
- External production noise disturbance transmitted via mechanical structure (test box) to the DUT

Modern test systems are multi-channel systems that can capture sound pressure, voltage, current and displacement in parallel.

Multiple microphones may be used to reveal defects that cannot be detected by a single test microphone. A typical example is testing audio systems such as sound bars, smart speakers or automotive subwoofer assemblies [12].

5 Signal Analysis

The goal of modern EOL testing is more than a simple separation of obviously good and bad sounding DUTs. To ensure high-quality standards and increasing reliability of the product all defects have to be detected that become worse over time. A short summary of meaningful analysis methods is presented in this section.

5.1 Fundamental Frequency Responses

The acoustic amplitude response over frequency is reflecting the acoustic output level and is crucial for EOL testing.

Acoustic phase measurements are important for polarity checks only. They are difficult to use at high frequencies where the influence of minor microphone distance variation is significant.

The essential information found in of the electrical input impedance can be summarized in the lumped parameters (T/S Parameter) which are easy to interpret and convenient for limit checking and statistical analysis. For loudspeaker systems with complex enclosures, the impedance magnitude can be a useful measure to check transducers, cross-overs and enclosure properties.

Generally, those responses accumulate numerous defects and can hardly be used alone to identify the root cause of a failed test.

5.2 Harmonic Distortion

5.2.1 *Lower Order Harmonic Distortion*

THD is a valuable, energy summing symptom for low order distortion reflecting the dominant nonlinearities such as $Bl(x)$ and $C_{ms}(x)$ of transducers [20].

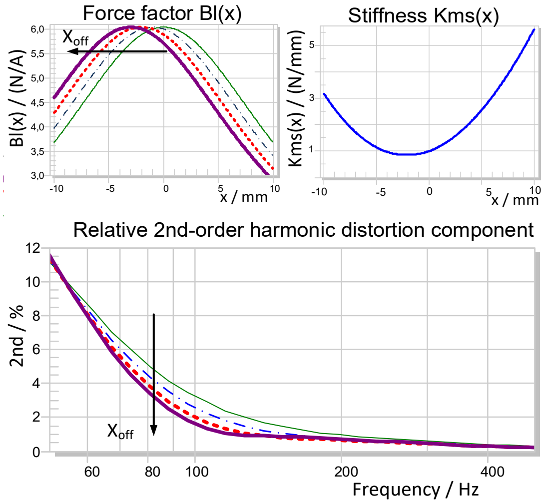

Figure 6: 2nd-order harmonic distortion measured in sound pressure output generated by the interaction between stiffness nonlinearity $K_{ms}(x)$ and an offset in the voice coil rest position of x_{off}=0, -1, -2, -3 mm.

2nd and 3rd order harmonic components correspond to the asymmetry and symmetry of all non-linearities inherent in the loudspeaker. Unfortunately, the 2nd order harmonic distortion is no reliable criterion for an offset in the voice coil rest position. Figure 6 shows an example where 2nd-order distortion decreases with rising coil offset X_{off}. The coil offset at X_{off}=-3 mm generates a significant asymmetry in the force factor Bl(x) shown as a thick solid line and compensates for symptoms generated by the asymmetry of the stiffness characteristic K_{ms}(x). Although an offset from the optimal voice coil rest position may reduce the harmonic distortion, the maximal positive and negative peak excursion without limiting may be reduced due to closer distance to the upper or lower boundaries.

5.2.2 *Higher-Order Harmonic Distortion*

Higher-order harmonic distortion (HOHD) evaluates the energy of spectral components at frequencies nf with n>7 which are multiples of the excitation frequency f as defined in IEC standards [2], [5]. This characteristic assesses the deterministic properties of the nonlinear symptom that occurs in the same way in each period. Hard limiting of the mechanical suspension or bottoming of the voice coil former at high excursion can be easily detected by HOHD.

However, this characteristic is less sensitive for other loudspeaker defects with random properties (e.g. voice coil rubbing, buzzing, air leakage noise) where the energy is equally distributed over all frequencies in the sound pressure spectrum. The characteristic HOHD does not exploit the phase of the higher-order harmonics which reflects the crest factor of impulsive symptoms generated by the loudspeaker defect in time domain.

5.3 Impulsive Distortion

Voice coil rubbing, buzzing, air leakage noise, loose particles and other irregular loudspeaker defects generate symptoms which have an impulsive fine structure. This becomes visible by inspecting the distortion components generated by the defect in the time domain. This can be easily accomplished by high-pass filtering the microphone time signal or applying an inverse FFT to the complex distortion spectrum at higher frequencies. The phase information of the distortion spectrum concentrates the energy in a fraction of one sine wave period generating a much larger peak value than than the rms value of the distortion averaged over one period. Regular nonlinearities in the motor and suspension and measurement noise generated by the microphone and electronic circuits are usually not impulsive and have a much lower crest factor (C<12 dB). Thus, the peak value measured in the time domain exploits the amplitude and phase information of both, harmonically and non-harmonically related distortion components providing maximum sensitivity of the EOL test system for all kinds of irregular loudspeaker defects with deterministic and random properties.

According to the IEC standard [2], the impulsive distortion is measured as the peak value in dB and is directly comparable to the SPL of the fundamental and other harmonic components.

5.4 Modulated Noise

Defect symptoms caused by small air leaks (glue problems in transducers) or excessive port noise (defective ports, vents) generate a modulated, wideband noise in the measured sound pressure signal. Using a demodulation technique, even hardly audible defects can be detected reliably [12].

This analysis applies to pure sine signals. However, with certain modification of the algorithm, it can also be applied to chirp signals. Consequently, no additional test step and hence test time is required.

5.5 Lumped Transducer Parameters

Frequency responses and harmonic distortion measures hardly provide data that can be interpreted as a distinct symptom for a physical root cause (e.g. a specific part of the DUT). Linear parameters (e.g. input resistance, resonance frequency, moving mass) and non-linear parameter (coil offset, stiffness asymmetry [3], [4]) are physically much more related to defect root causes.

Linear parameters [15] require electrical measurements which can be done in parallel to acoustic chirp tests whereas non-linear parameter measurement requires a multi-tone stimulus [16].

Furthermore, such parameters can also catch indications for potential defects. A typical example is the analysis of the voice coil position. A severe offset of the voice coil related to the optimal rest position initiates coil rubbing. This applies especially for headphones and micro-speaker that lack a spider as centering suspension element. The measured value of the coil offset in mm is the basis for process control to compensate small variation in the suspension properties by shift of the coil position during the assembling process.

Parameter measurements at EOL are also very useful for tuning signal processing of audio devices such as products using smart amplifiers that may require linear and non-linear parameter for optimal control.

6 Production Noise

R&D tests are performed in well-defined conditions without significant external disturbances; this is not the case at EOL. Acoustic and vibrational disturbances due to the production environment are not predictable and are in the same magnitude as the defect symptoms to be detected [8].

A schematic of the characteristics of typical acoustic ambient noise is shown in Figure 7. At lower frequencies, room modes dominate the disturbances with a more or less constant, high level. At higher frequencies, the long-term average is considerably lower, but impulsive or short-term disturbances caused by impacts, sirens, radio sets or squeak and rattle noise may have high instantaneous levels (>100dB SPL).

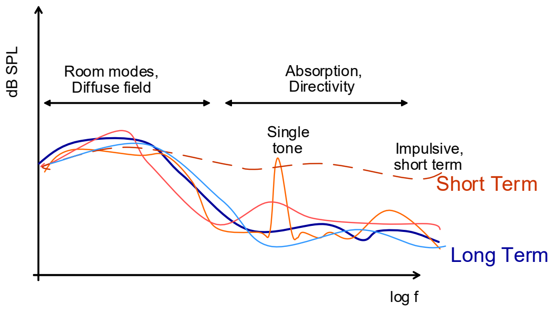

Figure 7: Typical noise in a production environment.

There are multiple strategies how to cope with production noise.

Typical passive solutions for insulation from disturbances are test cabins or enclosures. They should be well-damped for air-born noise and carefully decoupled from structure-born noise. Those enclosures may attenuate disturbances by up to 40dB. Whereas this is sufficient for amplitude frequency response and in most case also for THD, it is not sufficient for impulsive distortion (Rub&Buzz).

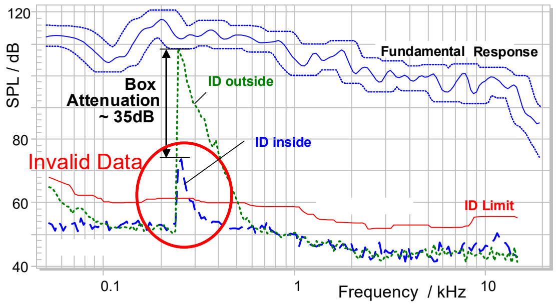

Figure 8: Detection of invalid data in a rub&buzz measurement by comparing the impulsive distortion (ID inside) at the test microphone with the impulsive distortion (ID outside) at the ambient noise microphone located outside of a well-designed test enclosure.

Figure 8 shows the corruption of the measurement signal at the test microphone by a impulsive ambient noise (clapping hands) outside a well-made test enclosure which provides almost 35 dB attenuation. However, this disturbance generates in impulsive distortion (ID) at the test microphone that exceed the allowed limit by 15dB and would cause a false Fail verdict.

Thus, in addition to insulation, further steps are required: Simple approaches such as an automatic repetition of a measurement in case of a failed test increases the test time by more than a factor of two and does not provide a reliable discrimination of the root cause (defect or production noise). The repeated measurement may be disturbed as well, so there is no reliable prevention from false verdicts. Also averaging (increasing number of periods or repetitions of tests) is not an efficient way, because it increases the test time significantly.

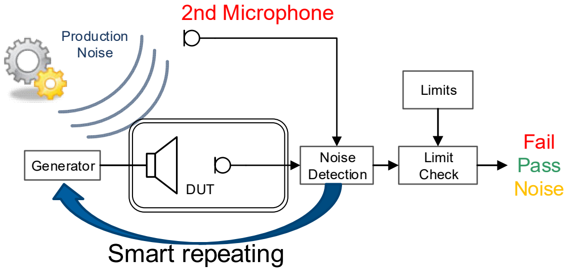

Figure 9: Test setup with a 2nd ambient noise microphone providing full immunity against external production noise

Using additional mechanical or acoustical sensors in parallel to the test microphone in the near field of the DUT, as shown in Figure 9, can be used for monitoring ambient noise and transforming this signal into an equivalent disturbance in the test box that can be compared with the test signal and the limit values to detect invalid data. If the ambient noise is random and not blocking permanently a frequency band the number of test repetitions can be minimized by merging valid parts of each repetition to a complete data set [8].

7 Limits

Limits are a crucial part of EOL testing. Important requirements for meaningful limits are reproducible measurements, optimal test stimuli and hence sensitive defect detection. Those requirements are discussed in detail in this paper.
A thorough discussion of limits, their calculation methods, updates and usage are beyond the scope of this paper. There are many useful references on this topic [8], [19], [18].

8 Timing in EOL-Testing

The total test cycle of an EOL test consists of

1. DUT positioning on test station
2. Fixing the DUT and connecting
3. Excitation of the DUT and signal acquisition
4. Release of DUT
5. Moving DUT out of test station, proceed with step 1

Initial setup and product changeover are ignored in this discussion since they are usually negligible relative to the total test time for large production batches. The actual measurement (point 3) is defined by the trigger of the test (barcode scan, hard- or software switch) until the test system has finished the measurement process itself (last captured signal sample). The final verdict may become available at a slightly later time without consequences on the cycle time as long as it does not delay the next test start.

8.1 Exploit Mounting Time

The test efficiency can be considerably increased when using an alternating test setup as shown in Figure 10. While one DUT is mounted, a second DUT can be measured. This method can even be applied for different types of products produced on the same production line as well. However, logistics and operation are more complex. An automatic detection of a connected DUT and test start helps to manage those challenges.

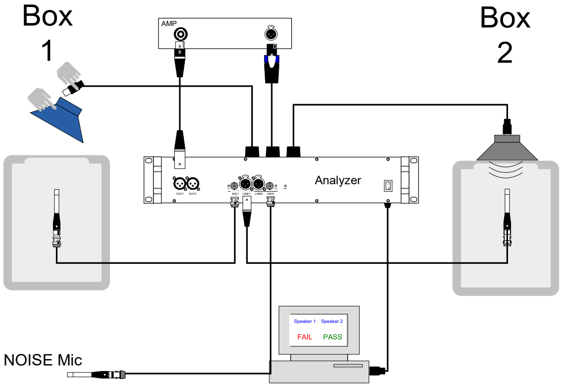

Figure 10: Alternating Test setup with two test stations controlled by one test system

Parallel testing of multiple DUTs is another option to improve the test efficiency. All of those considerations require modern multichannel test equipment and a sophisticated software solution.

8.2 Evaluation of Test Systems

Modern production of audio devices is fully automated and the EOL test is integrated in the process. Thus, the timing must be reliable and reproducible.
Most available testing solutions dedicated to EOL are sharing an operation system (Windows®, iOS®) with other applications, therefore the timing is not completely deterministic and needs to be evaluated. Comprehensive tools shall be provided by test equipment manufacturers to assess the performance and spread of test and analysis time.
Most important is the measurement time which is blocking the DUT at the test station. In Figure 11 a typical time distribution for a woofer test is shown. Assuming a gaussian distribution the standard deviation is about 7.8ms. That means that for one million tests no more than 3 tests have a higher variation than 50ms.

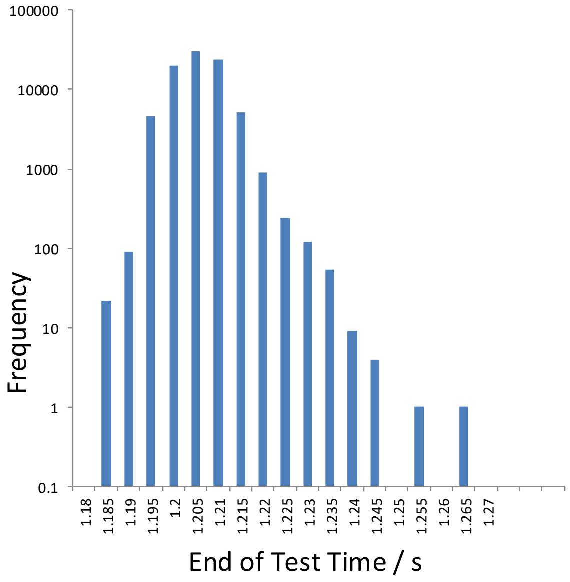

Figure 11: Time Spread of more than 87.000 test runs

9 Statistical Evaluation

Statistical evaluation should be applied to single value parameters for a consistency check of the production (Cpk/Ppk analysis, control charts).

Correlation studies can reveal dependencies of results on environmental conditions (temperature, humidity) [19].

Based on a statistical analysis of pre- or mass-production results, meaningful limits can be defined [8].

Result data history can be further evaluated for an online trend analysis, monitoring systematic drifts of results in order to generate a warning indication even before DUTs violate limits.

Defect symptoms contain valuable information about the design (R&D), components or raw material (supplier) and the production process. This data can be exploited by statistical and machine learning tools employing methods such as cluster analysis [8].

10 Conclusions

The paper showed that the measurement of basic characteristics for generating a Pass/Fail verdict can be accomplished in a very short measurement time by adjusting the stimulus to the transient behavior of the device under test. The step-sine stimulus provides an optimal frequency-time mapping but requires a significantly longer total measurement time compared to chirp signals to excite narrow band resonators. Consequently, the chirp with rising sweep speed at higher frequencies is the optimal stimulus for speeding up EOL testing. The time savings provide interesting opportunities for manufacturing:

If the test station gets the next DUT asynchronously from a waiting queue, the remaining time in each cycle can be buffered and used to repeat a test or to perform additional measurements.

Repeating parts of or the complete measurement is the best way to cope with a high probability of random ambient noise that cannot be attenuated properly by shielding, absorbers and other passive means. A second measurement is also useful to verify verdicts, that are close to the limits, especially if the impulsive distortion indicates a random nature of the defect (loose particles). This may significantly increase the reliability of the product.

Performing additional measurements can also provide valuable data for on-line diagnostics in order to control the manufacturing process. Machine learning and defect classification reveals the root cause of the failed unit. No human inspection of this unit is required if it is assigned automatically to a well-known defect class. A failed unit which represents the defect class in the best way can be selected automatically as a “golden defect” reference and can be used for training of EOL-operators or for deeper analysis by engineers. A failed unit which cannot be assigned to known defect classes should be investigated by an operator at a diagnostic station established close to the assembling line. Contrary to EOL testing, there is enough time to listen to the acoustical output of the DUT and dissemble the device in order to find visual clues for the unknown root cause.

Thus, the smooth combination of a fast and sensitive EOL measurement system with machine learning, automatic classification and manual testing of a few selected DUTs at the diagnostic station generates a learning process in manufacturing and engineering. This is both beneficial for maximizing the yield rate, improving the reliability of the product, and designing future products with higher performance cost ratio that are easier to manufacture.

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