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扬声器生产线终端测试

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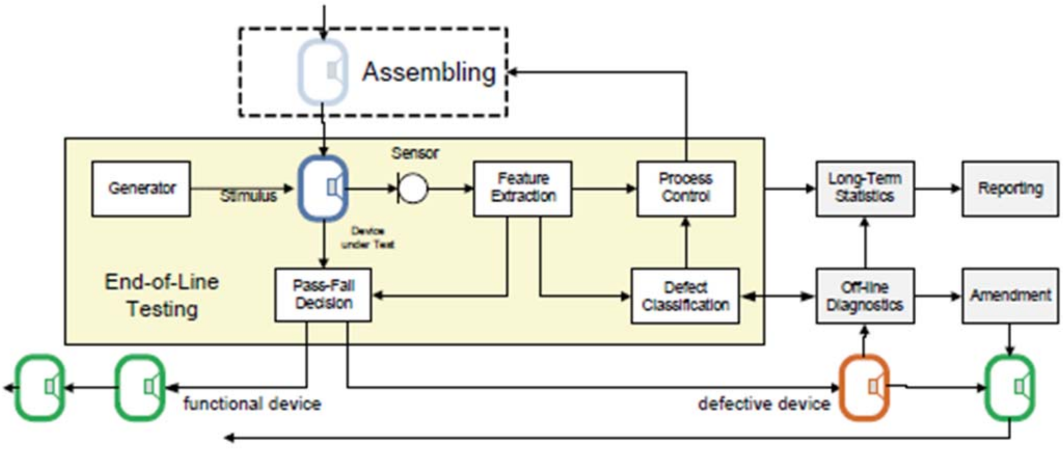
1. Introduction

Testing a manufactured unit at the end of the assembly line is a critical step in the production process. Defective products or even those not matching specification limits closely enough must be separated from the functional units shipped to the customer. End of-line testing assesses not only the quality of the product, but also the stability and yield of the production process. Reliable detection of non-functional units is the primary objective of the test, but reducing the rejection rate and maximizing the output is the ultimate goal. 100% automatic testing replaces more and more subjective testing by human operators to shorten the production cycle and to improve the reproducibility and comparability of the results. However, objective measurements should provide a comprehensive assessment as sensitive as a human tester using his visual and aural senses. To fully compete with an experienced operator, the objective measurement instrument should also have learning capabilities to accumulate knowledge about physical causes of the fault. Furthermore it should be capable of being integrated in automated lines, robust in a harsh and noisy environment, cost effective and simple to use.

1. 导言

在装配线的终端测试生产出的产品（或单元）是生产流程的关键一步，必须将有缺陷或者那些不符合规格上下限的产品要和发货给客户的功能齐全的分开。产线终端测试不仅要评价产品质量，也同时要评估生产流程的稳定性和合格成品率。能可靠地检测出不合格产品是测试的首要目的，但是降低报废率和成品率最大化才是终极目标。100%全自动测试代替越来越多操作员的主观判断以缩短生产周期和改善结果的再现性和可比较性（相似性），不管怎样，客观测试也应该能像人工测试员通过视觉和听力一样灵敏地给出综合评定。为能够完全匹敌有经验的操作员，客观仪器也应该具备学习能力去积累有关缺陷产品物理原因的知识，此外，它还应该兼具自动化、恶劣的噪声环境下得可靠性、高性价比和易操作等特性。



图示 1：生产线终端的品质控制

Modern end-of-line testing (EOL) which satisfies those requirements is a complex process, as illustrated in Fig. 1. This chapter can only give a general overview on essential components, their interactions and future trends. Fig. 1 provides a roadmap of the discussion, starting with the physical modeling of the device under test in section 2. This is the basis for ultra-fast testing, providing meaningful symptoms of the defect at high sensitivity. Important issues of the measurement will also be considered in section 3, such as the generation of a critical stimulus, the influence of the test conditions and the selection of optimal sensors. The following section 4 describes relevant features extracted by signal analysis, system identification and other kinds of transformations suppressing noise and redundant information. The Pass/Fail decision and classification of faults is the subject of section 5 and considers the problem of defining specification limits, grading the quality of the device and revealing the initial cause of the problem. The measurement results produced by end-of-line testing require a special data management and statistical analysis to support documentation, customer report and process control. The new requirements and technical possibilities in modern end-of-line testing put the future role of the human operator into question.

现代的能满足那些要求的产线终端测试（EOL），像图 1 所示，是一个复杂的过程。本章节只能给出对基本部分、它们的相互作用和未来趋势的一个总概述。图 1 提供了一个讨论的路线图，从第二部分的被测试设备的物理模型开始，能高灵敏地提供了有意义的缺陷症状是超快测试的基础，在第三部分也考虑了测量的一些重要事项，例如关键的激励信号的产生、测试条件的影响和最佳的传感器的选择。接下来的第四部分描述的是由信号分析、系统识别提取出的相关特性，以及其他压制噪声的变换和冗余信息。Pass/fail 的判决和缺陷的分类是第五部分讨论的内容，同时在这一部分还考虑定义规格上下限的问题以及设备质量的分级、揭示问题的初步原因。由产线终端测试产生的测量结果需要一个特殊的数据管理和统计分析来提供支持存档、客户报告和过程控制，在现代产线终端测试的新需求和技术可行性使得对产线操作员的未来的角色提出质疑（操作员未来应该被仪器取代）。

The discussion uses mass produced loudspeakers found in cellular phones, cars, multimedia, home entertainment and professional applications as a practical example. Some loudspeaker defects have a high impact on the perceived sound quality and will not be accepted by the customer. The loudspeaker example also represents other electrical, mechanical or acoustical systems manufactured at high quantities and low costs at a modern assembly line.

本讨论使用了大量生产的扬声器作为实际案例，它们被应用在手机、汽车、多媒体、家庭娱乐和专业应用中，一些扬声器缺陷对可感知的音质有很大的影响并且客户也不会接受。扬声器例子也代表其他在现代生产线大量和低成本制造的电子的、结构的或声学系统。

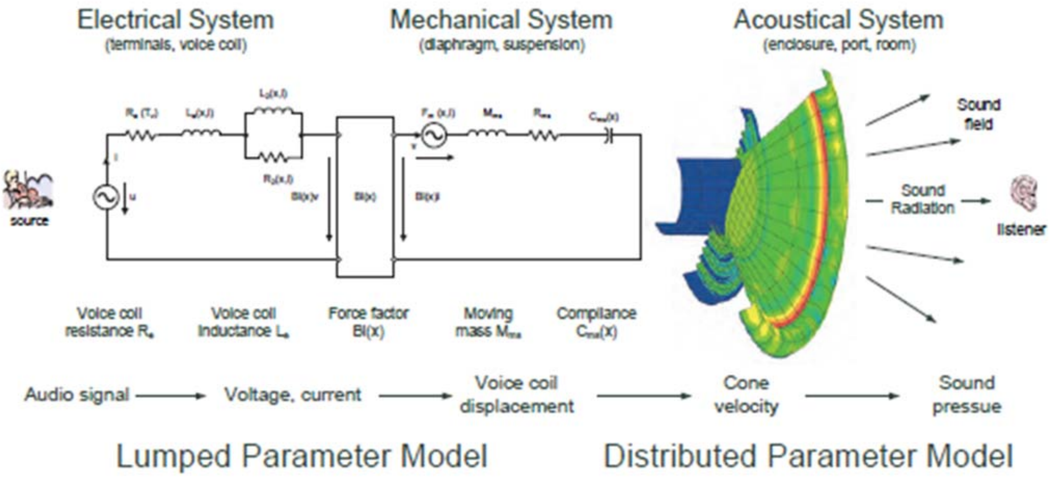


图 2.用集总和分布参数构成的电动扬声器模型

2. Physical modeling

A clear definition of the relevant properties and features of the device under test is essential for the end-of-line test to determine overall quality, perform fast measurements producing meaningful data and arrive at a correct Pass/Fail decision.

对被测设备的相关性能和特征的一个清晰定义是对产线终端测试来决定总体的质量、实现生成有意义数据的快速测量和做出正确的 PASS/FAIL 判断的基础。

2.1 Product in the development process

The models used in the design and development process are reliable sources of this information. For example the transfer behavior of loudspeakers can be described by two kinds of models as shown in Fig. 2.

用于设计和开发流程的模型是信息的可靠的来源，例如扬声器的电力声转换行为可以用图 2 所示的两种模型来描述。

The first model uses a small number of lumped elements representing the electrical resistance Re, inductance Le of the voice coil wire, force factor Bl(x) —one of the most important transducer characteristics— and other mechanical parameters such as the total moving mass Mms and the compliance Cms of the mechanical suspension. Those lumped parameters play an important role for the quality check of loudspeakers and can be easily identified from the electrical current i, voltage u and the mechanical displacement x. A second model is used to describe the generation of mechanical modes and acoustical waves using parameters distributed over the diaphragm and the sound field. Since the velocity and sound pressure may vary from point to point, it is impossible to measure the state of all those points on the radiator’s surface and in the sound field during end-of-line testing.

第一个模型用少数的集中参数元件来表示，如代表电阻的 Re、音圈线的电感 Le、力因子 BL(X)-（最重要的换能器特性）和其他一些力学参数，比如总的振动质量 Mms 和力学悬吊系统的顺性 Cms，那些集总参数在扬声器质量检验中扮演了一个重要的角色，并且能容易从电流 i，电压 u 和力学位移 x 中甄别得到。第二种模型是用振膜和声场的分布参数来描述机械模式和声波的产生，因为速度和声压可能在各点都不同，因此不可能在产线终端测试中来测量辐射器表面上和声场中所有点的状态。

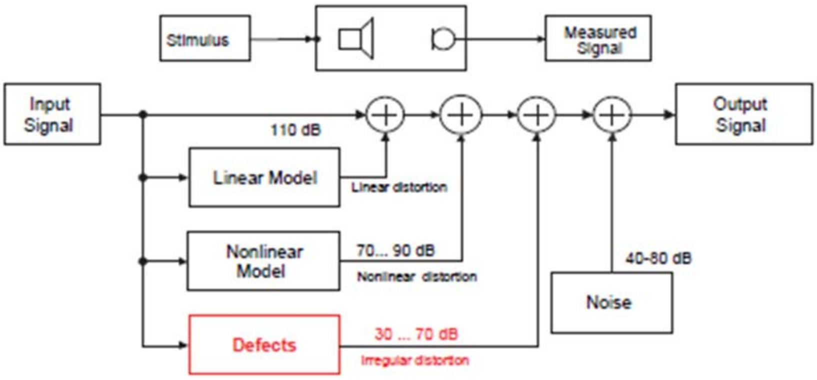


图 3.显示了一个扬声器系统中信号失真产生的信号流程图

A more abstract model depicted in Fig. 3 shows the signal flow between the signal source and the sensor output, and the generation of the following distortion components in the output signal:

Linear distortions are generated by the transfer response which varies in amplitude and phase with frequency. This kind of signal distortion is independent of the amplitude of the stimulus and describes the small signal behavior of loudspeakers. At higher amplitudes ***non-linear distortions*** are generated. These comprise new spectral components at multiples and combinations of the excitation frequencies. Measurement techniques assessing harmonic and intermodulation components exploit this property and play an important role in loudspeaker testing. All loudspeakers generate linear and non-linear signal distortions to a certain extent, depending on the physical limits of the electro-mechanical transducer. Those distortions are deterministic and can be predicted by numerical design tools (Klippel, 2006). The prototype at the end of the design process is a compromise between sound quality, maximal acoustical output, efficiency, size, cost and weight depending on the particular application. Those distortions are considered as regular and should be a feature of all replicated units passing the end-of-line test. Excessive signal distortions found in manufacturing are considered as *irregular distortion* and indicate a loudspeaker defect.

Ambient noise as found in a real production environment is also monitored by the test microphone and will corrupt the measurement. Those signal components differ in the sound pressure level significantly as shown in Fig. 3. Irregular distortion generated by a rubbing voice coil and other loudspeaker defects may be more than 60 dB below the total signal level and will still be detected by a human ear in the final application.

图 3 展示的是一个更抽象的模型，其显示的是在信号源和传感器输出之间的信号流程，和下列在输出信号中失真成分的产生：

线性失真是由转移函数响应产生的，表现为幅度和相位随频率变化。这种信号的失真与激励幅度无关并且用来描述扬声器的小信号下的行为。在更高幅度时就产生了***非线性失真***了，包含了激励频率的倍频及和频、差频等新的频谱成分，评估谐波和互调成份的测量技术就是利用了这种特性，并且在扬声器测试中扮演了一个重要的角色。所有扬声器产生线性和非线性信号失真到某种程度，取决于电动换能器的物理极限。那些失真是确定的并且是可以通过数值设计工具预测的（Klippel，2006），在设计流程最后出来的样板（模型）是根据特定应用场合所要求，在音质、最大声输出、效率、尺寸、成本和重量众多因素之间权衡折中的结果。那些失真被认为是正常的并且所有复制出产品理应存在和通过产线终端检测的一个特征。在生产制造中发现的多余的信号失真被认为是***不正常的失真***并能指出一个扬声器的缺陷。

正如在实际生产环境里发现的，***环境噪声***也会被测量传声器（麦克风）监测到并将破坏正常的测量，那些信号成份的声压级与如图 3 所示的显著不同。由擦圈和扬声器其他缺陷产生的不规则的失真也许在总信号电平 60dB 之下，并能够在最后应用中被人耳听得出。

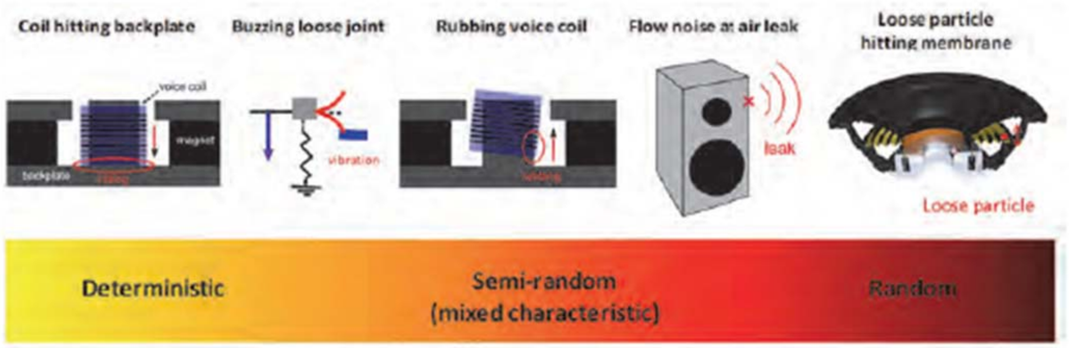


图 4.制造引起的扬声器严重的缺陷

2.2 Product in manufacturing

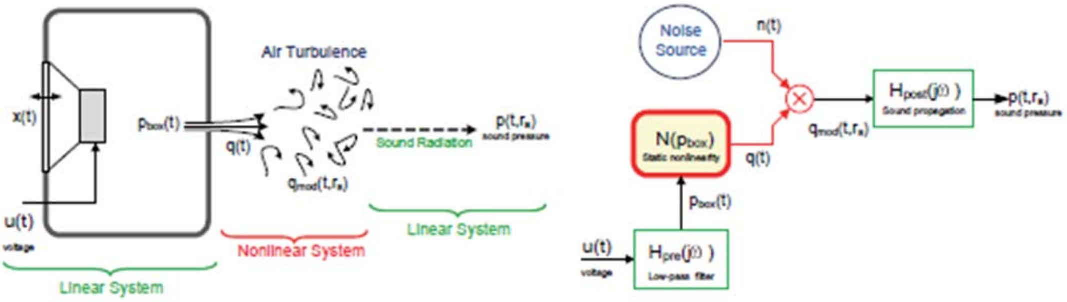
The variation in the linear and non-linear parameters provided by the physical models may be used for detecting defective units. For example, an increase of the moving mass (e.g., too much glue) or a decrease of the force factor (e.g., insufficient magnetization) reduces the sound pressure output of loudspeakers at higher frequencies. The relationship between causes and symptoms becomes more complex when initial and consecutive faults occur. For example, asymmetrical loudspeaker nonlinearities generate a dc displacement which moves the coil away from the rest position. This can cause audible distortion when the voice coil hits back-plate as shown on the left-hand side of Fig. 4. Other defects are hardly predictable, such as a poorly glued connection between the surround and the membrane behaving as an independent oscillator creating a buzzing sound. The spring-mass system performs an undesired mode of vibration at higher frequencies which is powered, triggered and synchronized by the stimulus. The faulty glue joint behaves here as a nonlinear switch activating the resonator above a critical amplitude. The beating of the braid wire on the loudspeaker diaphragm is a similar defect generating impulses at a particular position of the voice coil. The energy of those impulsive distortions is usually small and does not grow significantly with the level of the stimulus. A coil rubbing at the pole tips is a typical fault found in the production of loudspeakers generating impulsive distortion which contains deterministic and random components (Klippel, 2003). Air leaks in dust caps or in sealed enclosures emit a small air flow driven by the ac sound pressure inside the box which generates air turbulences and random noise (Klippel, 2010). Some loudspeakers defects behave randomly. For example, dust in the magnetic gap or below the dust cap in loudspeakers are accelerated by the cone displacement and hit the diaphragm at unpredictable times.

2.2 产品制造

物理模型中线性及非线性参数的变化或许可以用来检测不良品。例如，Mms值增大（可能是胶水过量）或Bl值减小（可能是充磁不足）而导致扬声器在较高频段声压输出降低。当缺陷发生并由此而产生各种不良，缺陷产生的根源和症状的关系就变得更加复杂了。例如，扬声器由于非对称而造成的非线性会产生一个直流偏置，使得音圈偏离平衡位置，造成音圈打底而出现可闻失真，如图4左侧所示。其它缺陷很难预测，例如折环和振膜连接处由于粘胶不良，形成了两个独立的谐振体，导致嗡嗡声。这样的弹性振子系统受到激励后，产生了不可预测的较高频率的振动模式。粘胶不良点起到的作用有如一个开关，当振幅超过某一临界值时非线性谐振受到触发。引线击打扬声器振膜的缺陷机理与此类似，它会在音圈某个特殊位置产生脉冲。这些脉冲失真的能量一般很小，并且不随激励信号的增加而显著增加。音圈与中柱顶端的擦碰是产线中一个典型的缺陷，它所产生的脉冲失真包含确定性和随机性成分（Klippel, 2003）。在音箱内交流声压的推动下，防尘帽或者封闭箱的泄漏会产生空气湍流和随机噪声（Klippel, 2010）。有些扬声器的缺陷具有随机性。例如，磁间隙或者防尘帽里面的粉尘会随着振膜的运动而加速，无规律地碰撞振膜。

Although some irregular loudspeaker defects produce symptoms which are not predictable and cannot be modelled completely, it is still beneficial to investigate the physics of those defects and to develop sensitive measurement techniques exploiting particular features of those symptoms. Fig. 5 illustrates this approach using the example of air noise generated by a small leak at the rear of a loudspeaker enclosure. The random noise is generated by turbulences due to the high velocity of the air at the exit of the leak. However, the air volume velocity q(t) is not constant, but a function of the sound pressure pbox(t) in the enclosure and the voice coil displacement x(t). The flow diagram on the right-hand side describes the generation by using a linear system Hpre(jω) generating the sound pressure signal pbox, a nonlinear modulation process and a second linear system Hpost(jω) describing the propagation of the generated noise to any point ra in the sound field. Information from the physical modelling provides the basis for a new demodulation technique for detecting air leaks more sensitive and reliable than the human ear.

尽管有些非常规缺陷产生不可预测并且无法完全仿真的症状，研究这些缺陷的物理特性，并为充分利用其特性而开发灵敏的测量技术还是非常有意义的。图5以一个后板有轻微泄漏而导致气流噪声的扬声器箱为例来说明这种研究方法。随机噪声是由空气泄漏时高速运动而造成的湍流所产生的。但是，这里空气的体积速度q(t)不是一个恒量，而是音箱内声压pbox(t)以及音圈位移x(t)的函数。图5右侧所示的流程图描述了随机噪声产生的过程，它用一个线性系统函数Hpre(jω)来表示声压信号pbox，一个非线性调制处理和一个二阶线性系统函数Hpost(jω)来表示产生噪声到声场中任一点 ra的传播。仿真模拟得到的信息是检测漏气新解调技术的基础，该技术比人耳要更加灵敏和可靠。



图示 5：音箱漏气产生的湍流噪声

3. Measurement

This chapter discusses the theoretical and practical aspects of performing the basic measurements, considering the measurement condition, excitation of the device under test and using optimal sensors to monitor relevant state variables.

本章节讨论基本测量的理论和应用，包括测量条件，待测设备的激励，以及通过优化传感器监控相关状态变量。

As expected from any other measurement process, the results of end-of-line testing should be repeatable under the same conditions, reproducible by a different operator at a different location using the same instrument, stable over time and free of bias. Repeatability and reproducibility can be tested by a gauge R&R test which reveals undefined factors that increase the variability of the measurement process. For example, loudspeaker transducers have to be clamped in the same way and at the same distance from the microphone, and should not be varied from measurement to measurement. The stability over time may be affected by climate conditions such as temperature, humidity and static sound pressure which affect the speed of sound. A critical issue in end-of-line testing is the accuracy of the measurement process producing bias-free results which agree with the “true” values and are comparable with the results of other instruments. The sound field generated by loudspeakers, for example, is influenced by the properties of the acoustical environment such as waves reflected from the table, floor, ceiling and room modes. Measurements performed in an anechoic room which are indispensable in loudspeaker design are usually not practical and too expensive in manufacturing. Measurement in a normal production environment using a simple test box is preferred but requires a special calibration routine to ensure comparability with the results of measurements in research and development (R&D). Instead of assessing absolute characteristics which might be easily a subject of a bias, it is more practical to use relative characteristics in end-of-line testing for defining the quality of the device under test. This subject will be discussed in the next chapter in greater detail.

如同任何其它测量方法，在相同条件下，在线终端测试系统的结果必须具有可重复性，不同操作员在不同地方使用相同的测试仪器具有可再现性，不同时间具有稳定性，并且没有偏差。可重复性和可再现性可以通过量具 R&R 测试法来检验，发现增加测量过程多变性的不明因素。例如，扬声器单元的固定方式必须相同，与麦克风的距离必须相同，重复测量的结果必须具有一致性。稳定性随着时间变化可能会受气候变化影响，如温度，湿度，以及与大气压相关联的声速。在线终端测试系统一个关键的问题是测量所得无偏差结果的准确度，它必须与“真”值相一致，与其它测试系统的测量结果具有可比性。例如，扬声器产生的声场受声学环境特性的影响，如桌面、地板、天花的反射以及房间的模态。在消声室进行测量对于扬声器设计来说是必不可少的，但对于生产来说可能就不切实际并且太昂贵了。在普通的生产环境中使用一个简单的测试箱来进行测试

比较容易实现，但必须经过一个特殊的校准程序来确保其结果与 R&D 中的结果具有可比性。在线终端测试系统中，采用相对值比绝对值对待测设备的品质进行评定更加有效，不易产生偏差。这个问题将在下一章中进行更详尽的讨论。

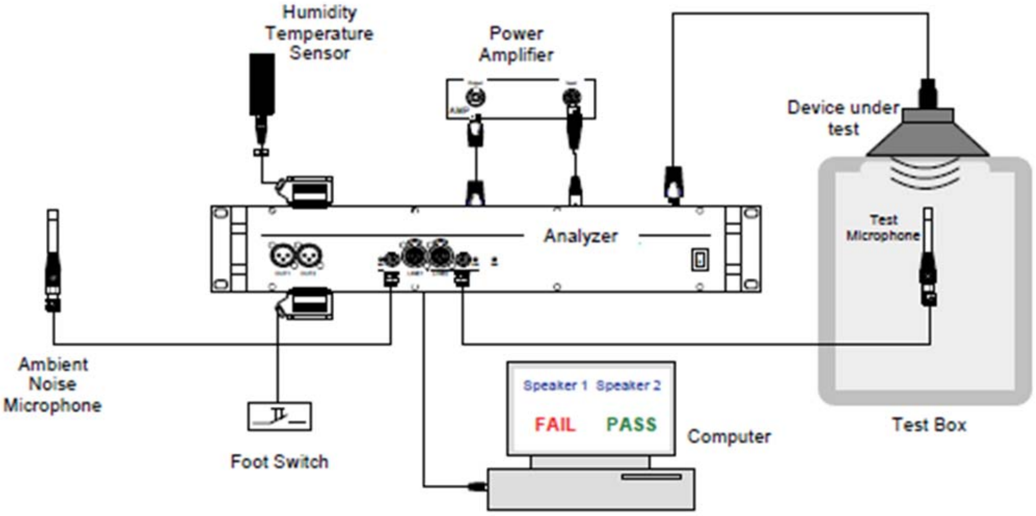
3.1 Test environment

Fig. 6 shows a simple and cost-effective hardware setup which complies with the requirements in the manufacturing of woofers, tweeters and other transducers used in audio systems. It comprises a front-end generating the stimulus, microphones, a power amplifier, a PC for processing the data and auxiliaries integrating the instrument into the production line. The loudspeaker is clamped at a clearly defined position on a rigid test box unable to perform any parasitic vibrations. The microphone measures the sound pressure in the near field of the transducer at a fixed (local) position. The test box also provides some shielding against ambient noise generated in a real production environment. However, the enclosed air volume in the test box behaves as an additional air spring which reduces the displacement of the voice coil at lower frequencies. Although the interior of the loudspeaker box is damped by lining the inner walls with absorbing materials, the radiated sound pressure output is also affected by standing waves. Thus the acoustical measurements performed in the test box are only accurate for the particular measurement setup used at the end of the assembly line and are not directly comparable with the absolute measurements made under other measurement conditions during the design process. This discrepancy has an important consequence on defining permissible limit thresholds in the Pass/Fail detection discussed below.

图6所示是一个简单有效的硬件配套，可以满足生产中低音、高音以及其它用于音响系统中换能器的测试要求。它包括一个前端激励、麦克风、功放，用于处理数据并将测试系统接入生产线的电脑。扬声器被固定在一个有明确标示的刚性测试箱上，不会产生任何寄生振动。麦克风固定在换能器近场指定位置进行声压测量。测试箱同时具有隔离生产线环境噪声的功能。然而，测试箱内的空气体积起到一个附加空气弹簧的作用，会减小音圈在较低频率时的位移。尽管扬声器箱内侧附有吸声材料，辐射声压输出还会受到驻波的影响。因此，在测试箱里所得到的声测量结果只相对于在指定的用于在线终端测试的设备上是准确的，并且该结果不能与设计阶段在其它测试条件下所得到的绝对值相比较。这个差异对于下面将会谈到的Pass/Fail上下限的定义起到重要的作用。

The measurement setup shown in Fig. 6 uses additional sensors to monitor production noise, air temperature and humidity. This information is crucial for detecting invalid measurements corrupted by ambient noise and to ensure long-term stability under varying climate conditions.

图6所示测试系统采用额外的传感器监控生产线噪声，空气温度和湿度。这些信息对于检测因受环境噪声影响而得到不可靠的测量结果有着至关重要的作用，同时它能确保不同气候下的长期稳定性。



3.2 Stimulus and excitation

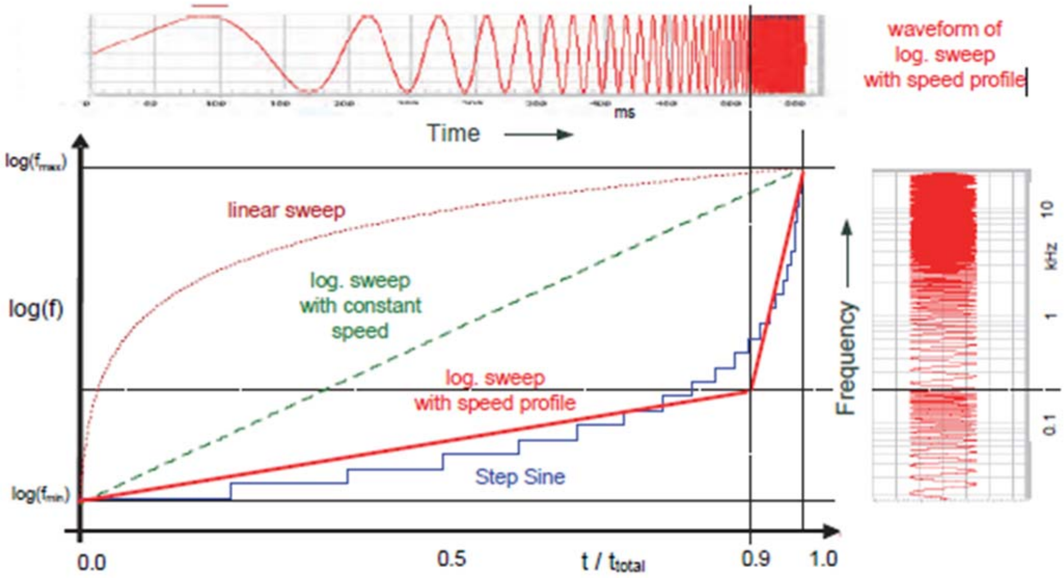
Most defects only produce significant symptoms if the device under test is operated in a critical state. An optimal excitation requires sufficient energy (e.g., ac main power) or a particular stimulus (e.g., analogue or digital signal). Ensuring sufficient excitation within the shortest time possible leads to ultra-fast testing which will be discussed in greater detail:

Loudspeakers are passive systems which require an electrical AC signal to produce an acoustical output. A sinusoidal stimulus excites the device at only one defined frequency and generates the fundamental component. All other frequency components found in the output spectrum can be identified as non-linear signal distortion or measurement noise. This measurement has to be applied to other frequencies within the audio band of interest (e.g., 20 Hz to 20 kHz) by stepping the frequency over discrete points with sufficient resolution (e.g., 1/10th of an octave) or by using a sinusoidal chirp sweeping continuously over all frequencies. The *stepped sine* stimulus stays at each frequency for a fixed number of periods (usually 5) to generate steady–state condition and to separate pre- and post-ringing after changing the frequency. Fig. 7 shows that the stepped sine stimulus spends most of the measurement time at low frequencies where the period length is long and both devices under the test and measurement instrument need a longer settling time. A complete measurement according to the minimal requirement can be accomplished within 1.5 s. Speeding up the measurement by reducing the number of test tones is not possible because the poor frequency resolution jeopardizes the excitation of loudspeaker defects behaving as narrow band resonators (e.g., buzzing parts not glued properly).

大部分缺陷仅当待测设备工作在临界状态时才会出现明显症状。一个理想的激励要求有足够的能量（如，AC电源）或者特定的信号（如，模拟或者数字信号）。下面将详细讨论如何在尽可能最短的时间内提供足够的激励而达到快速测量的目的：

扬声器是一个无源系统，需要AC信号激励从而产生声输出。扬声器在一个单正弦信号的激励下对应输出的基本成分也在该频率。输出频谱中包含的其它频率成分可以认为是非线性信号失真或者是测量噪声。这样的测量必须通过满足足够精度的阶跃离散频率（如每1/10倍频程）或者通过正弦Chirp连续扫频信号作用于目标音频范围（如20Hz~20kHz）内的其它频率。阶跃正弦信号在每个频率停留一定的周期（一般是5个）来产生稳态条件以及作为区分频率改变前后的标志。图7显示阶跃正弦信号的测量时间大部分集中在周期比较长的低频，待测设备以及测量仪器都需要一个较

长的稳定时间。根据最小精度要求，这样一个完整的测量时间需要1.5s。通过降低测量信号的精度以达到加快测量的目的是不可能的，因为频率精度不够的情况下，扬声器窄带谐振体类的缺陷可能无法受到激发（如由于粘胶不良导致嗡嗡声）。



图示6：产生器产线终端测试的标准硬件配置

Continuous sweeps excite all frequencies using a defined mapping between instantaneous frequency and measurement time. The *linear sweep* passes the low frequencies quickly and spends most of the time at higher frequencies. The measurement time should be about 20s to provide sufficient resolution at low frequencies according to minimal requirements. The *logarithmic sweep* with a corresponding frequency-time mapping reduces the measurement time at higher frequencies for the benefit of lower frequencies accomplishing the measurement within 0.4 s. However, the measurement time can be reduced even further to 0.2 s by using a *sinusoidal sweep with speed profile* as illustrated in Fig. 7. This stimulus comprises logarithmic sections with different sweep speeds and approximates the preferred frequency-time mapping of the stepped sine stimulus. It spends 90% of the measurement time below 200 Hz to activate all kinds of irregular loudspeaker defects and passes the high frequency range at a 10 times higher sweep speed.

连续扫频通过即时频率与测量时间的映射来激发所有的频率。***线性扫频***低频段的扫描时间很短，大部分时间集中在高频段。根据最小精度要求，低频要达到足够精度的最短测量时间是20s。***对数扫频***通过频率-时间映射法减少高频段占用的测量时间，增加了低频段占用的测量时间，相应的最短测量时间是0.4s。然而，通过***在正弦扫频的基础上增加一个速度配置***可以进一步将测量时间缩短至0.2s，如图7所示。这种激励包括扫频速度不同的对数段，类似于通过频率-时间映射的阶跃正弦信号。200Hz 以下占用了90%的测量时间，足以激发各种各样的扬声器非常规缺陷，而高频段则以10倍于低频的扫描速度进行快速扫描。

Although the sinusoidal sweep with speed profile is a convenient stimulus for ultra-fast testing of audio equipment and other electronic devices, it cannot assess the intermodulation distortion generated by non-linearities in the device under test. A sparse multi-tone signal comprising a multitude of distinct tones at a defined spectral distance and pseudo-random phase produces a noise-like stimulus which has properties similar to a steady-state audio signal, generating all kinds of harmonic and intermodulation distortion components in the output signal. This stimulus is ideal for assessing the large signal performance of loudspeakers and to identify motor and suspension non-linearities. Music, speech and other natural audio signals play an important role in systematic listening tests during the design phase but play a minor role in stimulating devices during end-of-line testing because those tests are inferior with respect to sensitivity and speed.

变速正弦扫频信号能够满足音频仪器和其它电子设备的超快速测量要求，但它无法评估待测设备非线性所产生的互调失真。一个稀疏多频信号包含多个不同频率信号，具有可定义的频谱间距和伪随机相位，类似于噪声信号，具有稳态音频信号的特性，可以在输出信号中产生各种谐波和互调失真成分。这种信号非常适用于评估扬声器大信号特性以及检测磁路和悬挂系统的非线性。音乐，语音和其它自然的音频信号在设计阶段的系统听音测试中起到举足轻重的作用，但不适于作为在线终端测试的激励信号，因为它们在灵敏度和速度方面都有所欠缺。

3.3 Sensor system

Monitoring relevant state variables of the device under test is a further requirement for achieving high sensitivity in end-of-line testing. This question is closely related to the selection of optimal sensors and can be answered by using information from physical modeling as discussed in section 2. For example, the state of a loudspeaker can be observed in the electrical, mechanical or acoustical domain.

在生产线终端的测试中，如果我们想要更高的测试精度，我们需要实时测量相关状态变量。这个问题与我们选择的理想的传感器紧密相关。关于这个问题的答案，我们可以参考在第二节中我们讨论的物理模型。例如，扬声器的状态我们可以在电类比，力类比或者声类比中观察。

The acoustical measurement is indispensable for detecting air leakage noise and other impulsive distortion generated in the mechanical and acoustical domains which also have a high impact on the perceived sound quality. However, the sound pressure signal is less suited for assessing the properties of the electrical and mechanical system modeled by lumped parameters as shown in Fig. 2. A simple measurement of the electrical signals at the loudspeaker terminals provides results which are more reliable and easier to interpret. The direct measurement of mechanical state variables by scanning techniques is important for assessing the cone vibration during the design process, but until now has played a minor role in end-of-line testing. However, inexpensive triangulation lasers are already being used for testing spiders, passive radiators, diaphragm and other mechanical loudspeaker parts on the assembly line.

关于声学测量我们必须要测量漏气噪声以及其他由电或声引起的对音质有巨大影响的冲击失真。然而，声压信号并不是非常适合用来评估电和力的系统，如图 2。相比之下在扬声器输入端口测量的电信号更可靠也更容易解读。在设计阶段，通过扫描技术直接测量的结构状态参量对评估锥形纸盆的震动十分重要。但是，目前为止这种测试在产线终端的测试中仍然处于相对次要的地位。而另一方面，在装配线上，并不昂贵的三角激光测量已经被用于测量弹波，被动盆，振膜以及其他的扬声器部件。

Multiple sensors combined into an array (e.g., microphone array) and parallel acquisition of the sensor output signals are required to localize the position of the defect in a sound field or a mechanical structure corresponding with a distributed parameter model. The number of sensors and locations in a sensor array depends on wavelength of the signal components and the distance to the source. The position of defects generating deterministic symptoms can also be determined by repeating the measurements while changing the position of the sensor.

使用多个传感器组成的阵列，平行获取每个传感器的测量数值可以测得声场中具体存在缺陷的位置，或者是机械结构中的缺陷的位置。传感器阵列的传感器数量以及每一个传感器的位置取决于待测信号的波长成份和信号源到传感器阵列的距离。更改传感器位置多次重复测量可以非常确定的测得该缺陷的位置。

4. Feature extraction

The objective of signal analysis is to extract features from the monitored signals which reveal the symptoms of the defect, to remove redundancy in the data and to suppress information not relevant for the quality assessment. This section can only give a short overview on plurality of traditional and new methods used for end-of-line testing.

测量数据分析首先要在测试得到的信号中选取出能够揭示系统缺陷特征的测试数据，去除无关的数据，压缩不相关的数据。本章对生产线终端测试中使用的传统方法和新方法作一个概述。

4.1 Signal analysis

The first class of methods as summarized in Table 1 are applied to the time signals at the sensor outputs. There are no assumptions made as to how the device under test is excited and what properties the stimulus has. There is also no physical model of the device required. Thus the signal analysis is the most general approach which can be applied to all kinds of devices under test.

第一类信号处理方法是用来处理传感器接收到的时域信号，在表1中列出。对于这类方法我们无需假定待测品是如何被激励以及激励信号的属性如何，待测系统也无需符合任何物理模型。因此，这类方法是可用于所有待测系统的方法。

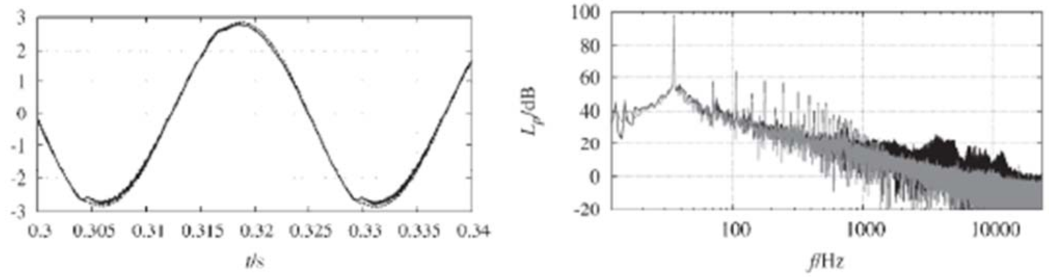
Signal Characteristic 信号特征参量	**测量方法及诊断值**
RMS 值(RMS value)	与信号的能量直接相关，这是一个简单且敏感的参数，可用于测量一些确定的参量 deterministic processes（例如：扬声器灵敏度的差异）
峰值 (peak value)	时域信号在一段时间内的最大绝对值，比如一个周期内。这个参量在评价冲击失真（RMS 值很小）时非常有效。（比如异物颗粒 loose praticles）
峰值因数(Crest factor)	峰值和 RMS 值的比值，用来描述信号的冲击性（impulsiveness），与信号的幅度无关。（峰值因数大于１０dB 显示扬声器有缺陷）
自相关函数$\psi(\tau)$ (Autocorrelation)	一个时域信号 x(t)和 $x(t-\tau)$ 的相关函数。使用一个大的 τ 值使结果呈现周期性 gives information about repeating events
相关系数(Coherence)	对两个时域信号作互相关谱并且用两个信号自己的自相关函数作归一化，用于表述两个信号的相互关系。该参数可以用来检测传感器阵列中由于周围环境噪声引起的无效的测试信号(Bendat & Piersol, 1980).
周期性 (Periodicity)	可由信号自相关函数的峰值因数来计算得到，数值越高代表信号的重复性越强（例如电动马达声）
周期长度 T	自相关函数两个最大峰值间的时间长度，取决于信号中最低的频率成分。generated by a deterministic process (e.g., revolution of a car engine)
同步求平均 (Synchronous average)	用于描述信号中的周期成份，衰减了信号中的随机非周期成份（例如：周围环境噪声）
随机冗余 （Random residual）	原始时域信号和同步平均的差，用于时域描述信号中的非周期随即成份。（例如：散落微粒，漏气噪声，外部噪声）. (Klippel, 2010)
倒谱（Cepstrum）	信号对数频谱的反傅里叶变化(Oppenheim & Schafer, 2004)，可用来反卷积声源信号或者脉冲响应，以描述声信号传播。（例如：车体的声辐射）

信号包络（Signal Envelope）	使用希尔伯特变换对信号反调制，得到解析信号的幅度。用于检测半随机因素造成的缺陷（例如：调制的漏气噪声）(Klippel, 2010).
离散傅里叶变换Discrete Fourier Transform (DFT)	对于一假定周期信号，分析其线性频响。离散傅里叶变换适用于实时分析周期信号，变换长度设为信号周期 T 的整数倍（例如：打底）
短时傅里叶变换Short-time Fourier Transform (STFT)	一种时域至频域的分析方法，对时域信号加窗后再进行离散傅里叶变化。该方法主要用于非稳定信号，需要信号有较高的出现频率或者有高度的时间分辨率（high temporal resolution）(Boashash, 2003).
离散小波变换Discrete Wavelet Transform (DWT)	根据分析频率的不同使用小波进行的时域至频域的分析方法。该方法适用于非稳态信号，我们可以在低频得到较高的频率分辨率，而在高频得到较高的时间分辨率。(Percival & Walden, 2000).

表1:信号分析的重要参量

The applications of the signal analysis techniques will be illustrated on a sound pressure signal measured in the far field of a loudspeaker system having a small air leak. The diagram on the left-hand side of Fig. 8 shows the signal waveforms radiated by the defective loudspeaker as a solid line and the waveform of the same loudspeaker where the leak is sealed as dashed line.

我们用以下一个例子来阐述这种信号分析的方法：一个有少量漏气的扬声器系统，我们在远场测试声压信号。图 8 的左图实线为有漏气的扬声器系统的声信号波形，虚线为不漏气的扬声器系统的声信号波形。



图示8：上图为使用35Hz 正弦波测试漏气箱体（黑色实线）和密封箱（灰色虚线）得到的波形（左图）和频谱图（右图）。

The loudspeaker without leak generates a smoother waveform but there is neither significant difference in the peak nor in the rms value. The autocorrelation function calculated from both signals reveals high periodicity and a period length of 28.5ms. The discrete Fourier transform (DFT) applied to the both time signals which are exactly 128periods long provides the line spectra shown in the right hand side of Fig. 8. There are distinct spectral components at f0=35 Hz and at multiple frequencies fn=nf0 with 1<n<20 with almost the same sound pressure level (SPL) for the functional and defective unit shown as black and grey lines, respectively. The air leak generates a higher sound pressure level for spectral components above 1 kHz. The power of the symptom is very low (-80 dB) and distributed over a wide frequency range causing a low spectral power density close to the noise floor of the measurement system. Therefore it may be more beneficial to attenuate the low frequency component below 1 kHz and to transform the high frequency component back to the time domain by using an inverse DFT. This corresponds to high-pass filtering of the original sound pressure signal revealing useful symptoms of the air leak.

两者相比，无漏气的扬声器系统的测试波形更平滑，但是两者的信号 RMS 值和峰值都没有明显区别。两种信号的自相关函数显示两者都有很强的周期性，周期为 28.5ms。对于这两组时域信号，

我们分别取其 128 个周期长度并作离散时间傅里叶变换（DFT），得到两者的频谱如图 8 的右图。在频谱中我们看到明显的基频成分 f0=35Hz，以及其他成份 f0=nf0(1<n<20)，两者的频响基本一致（黑色频响为不漏气扬声器系统，灰色为漏气的扬声器系统）。而对于 1kHz 以上的频率部分，有漏气的扬声器系统的声压级高于无漏气的系统。由于这些高频部分的声压级很低（约-80dB），而且覆盖的频率范围很广，因此频谱的能量密度很低，接近测试系统的本底噪声。因此更有效的方法可以是通过对频域信号的反离散傅里叶变化，设计一个高通滤波器，以此来减少信号源中的 1kHz 以下的低频成份。如此，漏气和不漏气的扬声器系统的差别会更为明显。

4.2 System analysis

Many devices under test (such as loudspeakers) can be considered as transfer systems requiring an input signal for excitation and generating an output signal closely related to the stimulus, but containing additional signal distortion as shown in Fig. 3. Using a particular test signal with particular properties, the monitored sensor signal can be split into linear, nonlinear and irregular distortion components, providing further characteristics for end-of-line testing as summarized in Table 2.

许多被测器件（如扬声器）均可被视做一个转换系统，需要一个输入信号进行激励，生成一个输出信号。该输出信号一方面与输入激励信号密切相关，一方面也包含了附加的信号失真（如图 3 所示）。使用一些特殊属性的特殊信号，监测到的信号可分解为线性失真，非线性失真和不规则失真成分。表 2 详细总结了产线检测的各种特征参量。

系统特征参量	测量方法与诊断评估
基频成份的振幅响应	在小振幅时符合振幅线性响应函数，在小信号时显示缺陷。（如鼓纸质量差异）
基频成份的相位响应	在小振幅时符合相位线性响应函数，对检测时延（如麦克风距离）及极性较为重要。
总谐波失真（THD）	描述谐波成分（激励频率整数倍）的 RMS 幅值，可显示主要的非线性因素如扬声器机械悬挂系统刚性的非线性。
总谐波失真加噪声	描述去除基波成分后的信号 RMS 幅值，表现非基波整数倍频的非线性失真及扰动。
二次谐波失真	显示非对称结构的系统固有的非线性，如扬声器机械悬挂系统在正向和反向位移时的刚性差异。
三次谐波失真	显示对称结构的非线性，如机械悬挂系统的对称限幅。
高阶失真峰值	使用频率为 f0 的正弦波激励信号进行测量，将接收到的信号进行截止频率为 fc >10f0 的高通滤波，在时域内以周期 1/f0 检测峰值。该特征参量测试所有确定性和随机性脉冲失真时均非常灵敏。（例如音圈擦圈。）
高阶谐波失真峰值	用频率为 f0 的正弦波激励信号进行测量，将接受到的时间信号仅对 10 次谐波以上的部分以周期 1/f0 检测峰值。该特性可诊断由确定性因素造成的脉冲失真。（例如音圈打底。）
非谐波高阶失真峰值	使用频率为 f0 的正弦波激励信号进行测量，将接收到的信号进行滤波提取 fc >10f0 的高阶非谐波成分，在时域内以周期 1/f0 检测峰值。该特征参量可诊断由随机因素造成的随机脉冲失真。（例如游离颗粒造成的异音）
非谐波失真包络峰值	使用频率为 f0 的正弦波激励信号进行测量，将接收到的信号进行滤波提取 fc >10f0 的高阶非谐波成分，对多周期平均解调信号包络读取峰值。该特征参量可诊断具有随机性结构同时又具有确定性包络的半随机因素失真（例如漏气引起的噪声）。
多音调失真	以稀疏的多音调信号进行激励，从接收到的输出信号中提取并非由激励信号所激发出的成份。该方法可测试出谐波失真和互调失真，对检测力系数的非线性（例

	如音圈偏位）非常灵敏。
不一致性	描述输出信号与输入信号之间的线性偏差（与一致性互为补数）。该特征参量可使用音乐，对白及其它任意密集频谱信号进行激励，反映出各种失真和噪声。

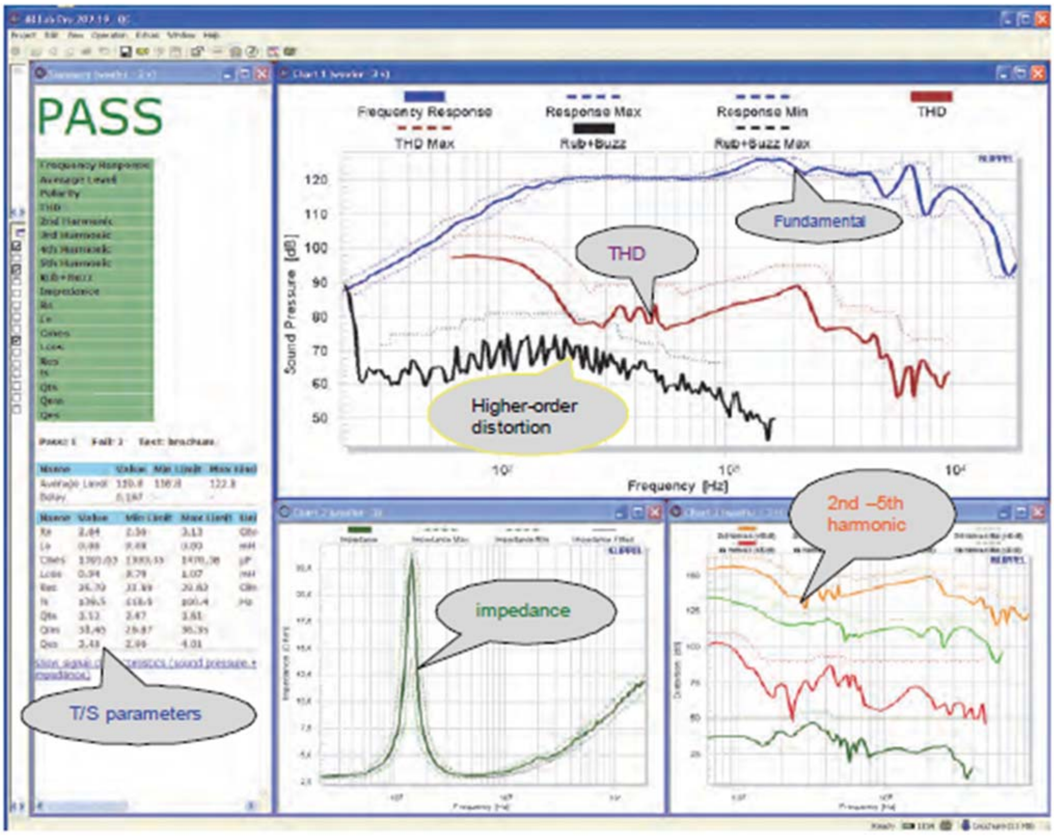
表 2：系统分析方法的特征参量分类

Exploiting the properties of the stimulus, the spectral components found in the signal analysis may be interpreted as fundamental or distortion components. The sound pressure signal of the loudspeaker with and without air leak in Fig. 8 has been excited by a sinusoidal test tone at f0=35 Hz. Thus the lowest frequency component found at this frequency is the fundamental component which dominates the total sound pressure signal. The phase of the fundamental component reveals polarity of the loudspeaker and may be used for checking the correct connection of the electrical terminals. The spectral components at multiple frequencies fn=nf0 with n≥2 are the nth-order harmonic distortion components generated by the nonlinearities inherent in the device under test. The energetic summation of those components gives the total harmonic distortion THD. The symptoms of the air leak are not only higher-order harmonics (n>20) but also spectral components at other frequencies. Repeating the signal analysis for other excitation frequencies leads to the frequency response of those components.

通过选用特性适宜的激励信号，接收到的信号频谱可分为基波部分和失真部分。图8描述了以35Hz正弦波为激励信号时，音箱漏气时 和不漏气时所测得的声压频谱。其中最低的频率成分是基波，在声压信号频谱中占绝对优势。从基频的相位可得知扬声器的极性，因此可用来检测接线端子的连接是否正确。频谱成分中满足fn=nf0 （n≥2）的部分即为被测器件的非线性所导致的n次谐波失真。这些谐波成分的能量总和即为总谐波失真THD。图中的漏气症状不仅表现为高次谐波失真(n>20)，同时也形成了其它非倍频成分。用其他频率的激励信号进行重复分析可测得这些频响成分。

Fig. 9 shows the frequency responses of the SPL fundamental, 2nd-5th harmonics and the total harmonic distortion in the sound pressure output using a short logarithmic sweep with speed profile as shown in Fig. 7. The roll-off of the fundamental component at the cut-off 100 Hz limits the usable audio band at lower frequencies, while the break-up modes cause the peaks and dips at higher frequencies. The motor and suspension nonlinearities cause a high value of THD at low frequencies. The higher-order distortions curve is 45-60 dB below the fundamental and shows that the device under test has no impulsive distortion generated by a rubbing coil or other irregular defects.

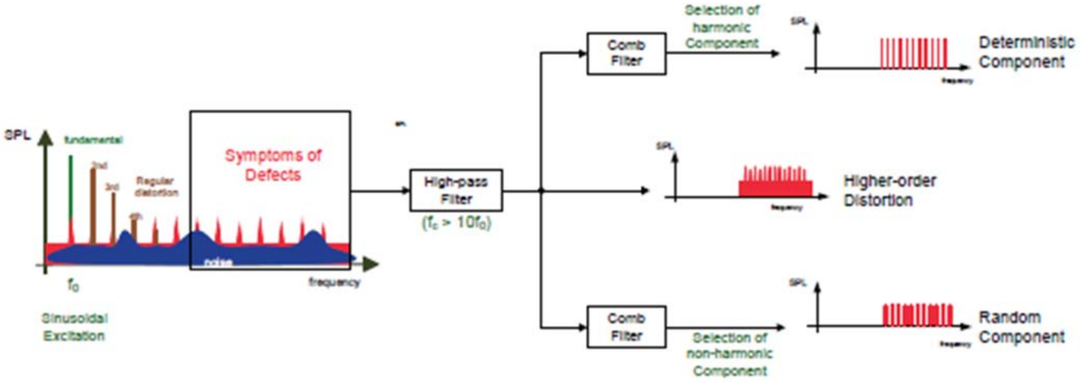
图 9 所示为输出声压中的基频声压级频率响应、二到五次谐波失真和总谐波失真。此处使用的是短时对数扫频信号和图 7 中所示的速度廓线。基频成分在 100Hz 处的滚降限制了低频的有效频宽，分割振动模态也造成了高频峰谷。驱动系统和悬挂系统的非线性造成了低频部分较高的总谐波失真。本实例的高次谐波失真曲线低于基频成分约 45~60 分贝，说明被测器件不存在由音圈擦圈或其它不规则因素造成的脉冲失真。



图示9：用时长200毫秒的激励信号超快速测试扬声器

To increase the sensitivity of the end-of-line measurement and to identify the physical cause of the defect further features have to be derived from the measured signals. Synchronous averaging over adjacent periods provides the deterministic component at a higher signal-to-noise ratio while suppressing measurement noise and other random components. This can also be realized by a comb filter selecting all harmonic components in the high-pass filtered signal as shown in Fig. 10. The complementary signal comprising only non-harmonic components is a random signal.

为了提高产线检测的灵敏程度并且确诊缺陷的物理成因，我们需要从测得信号中获得进一步的特征信息。临近周期同步平均法可以减小环境噪声及随机噪声的影响，获得较高的信噪比和更为确切的测量结果。另一种方法如图 10 所示，将测得信号做高通滤波，再对其进行梳状滤波提取其中的谐波成分，剩余的非谐波成分即为随机性失真信号。



图示10：采用正弦激励信号分离确定性失真和随机性失真

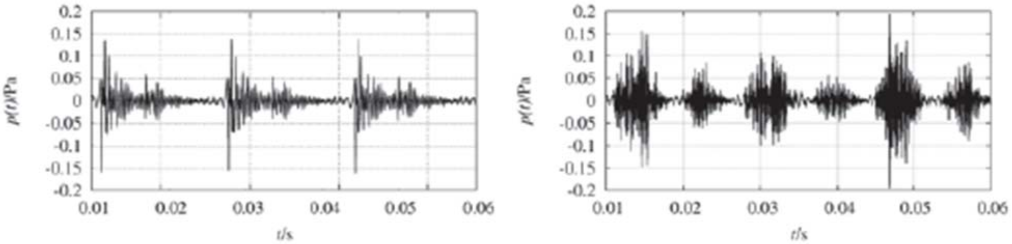


图11：胶水粘结不牢引起的确定性失真（ 左）和腔体漏气引起的随机性失真（右）

Fig. 11 illustrates the benefit of this separation on a loudspeaker having two defects. The periodic waveform in the left diagram reveals a deterministic defect caused by a buzzing loose joint while the random component on the right side is caused by an air leak in the enclosure. Turbulent noise generated at the leak has a completely random fine structure, but the envelope of the noise is deterministic due to the modulation process discussed in Fig. 5. Since the amplitude of air leakage noise is very small and in the same order as ambient noise (e.g., air conditioning) a measurement technique which accumulates the energy over time is required. Direct averaging of random distortion signals over multiple periods will reduce the noise signal and reveal no meaningful symptoms. Demodulation of the random distortion signal and synchronous averaging of the envelope as shown in Fig. 12 provides a sensitive feature for detecting semi-random noise reliably (Klippel & Werner, 2010).

由图 11 描述了当扬声器有两种缺陷时使用分离分析法的优越性。左图中的周期波形可诊断为胶水粘结不牢所引起的确定性蜂鸣失真。右图中的波形可诊断为音箱腔体漏气引起的随机性失真。漏气处的气流扰动噪声表现为纯随机结构，但其噪声包络却表现出特定周期性，原因是图 5 中曾提及的互调过程。由于漏气噪声幅值较小，几乎与环境噪声（例如空调）处于一个层次，于是需要一个巧妙的方法将时域内的能量积累起来。直接对多周期内的随机性失真信号求平均值将会稀释失真信号从而掩盖症状。在这里我们可以将测得的信号进行如图 12 所示的解调检波，将噪声包络进行同步平均，即可更加灵敏可靠地检测出半随机性失真。

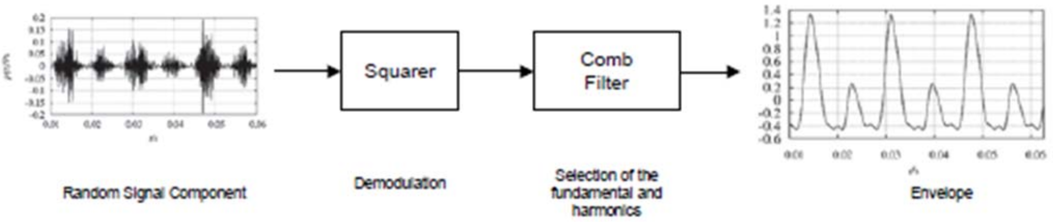


图 12. 通过对随机信号进行解调检波并对噪声包络取同步平均的方法检测漏气造成的扰动噪声

4.3 Model identification

Exploiting available a-priori information on the physics of the device under test provides further features for end-of-line testing. These are more closely related to the material and geometrical properties of the device. Table 3 gives an overview on those characteristics:

研究被测器件的固有物理信息可使产线检测更为全面。这些信息与被测器件的材料和几何属性密切相关。这些特征参量的概括见表 3：

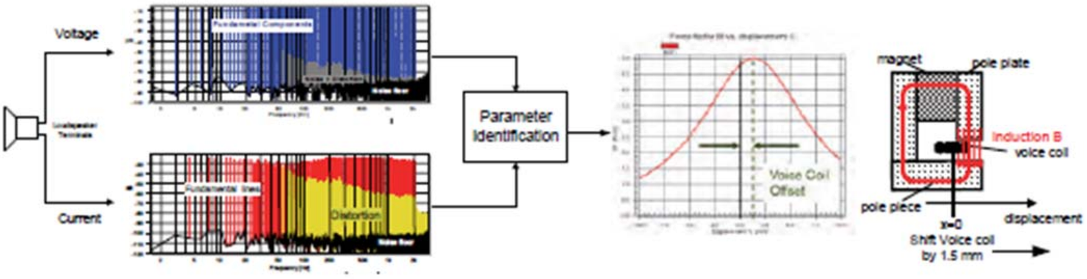
特征参量	测量方法与诊断评估
参数	通过核定测得信号与预估值之间的差异，结合成本函数，可以定义模型参数。预估参数值与所用的激励信号无关，仅用于描述被测器件的性质。这些参数有其物理意义（如力系数 BL），且会随着材料特性及几何形状的差异（如音圈偏位量）而发生变化，也可用于做制程控制。
状态变量	可通过特殊的激励信号，结合模型和既定参量进行计算。这在对产线检测中不易测得或需要昂贵仪器（如激光头）方可测得的状态变量（如音圈位移）进行评估时表现优秀。
信号失真	可通过特殊的激励信号，用既定模型分析线性和非线性成分。该技术需将良品单元的规则失真与仅存在于不良品单元的缺陷失真（如游离颗粒）分离开来。
降低误差后的变量	由初始变量（如谐振频率）并对温湿度及其它外部因数补偿而计算得出。这种对气候影响的补偿需要在产线上在安装温度计等感应器件，并且需要特定条件的判别模型。该方法在测得的变量中减除了温湿等普遍原因引起的部分，因此允许使用更严格的规格限定。

表 3：产线系统检测方法

Linear system identification has a long history in loudspeaker measurement and can be realized by fitting the predicted electrical impedance based on the lumped parameter model in Fig. 2 to the measured impedance response. The best estimate of the free model parameters are the Thiele/Small parameters (T/S) are shown on the lower left hand-side of the screenshot Fig. 9. Those parameters include the voice coil resistance, resonance frequency and Q factor and are easy to interpret. However, the linear model is limited to the small signal domain and cannot explain the generation of nonlinear distortion at higher frequencies. Nonlinear system identification exploiting the nonlinear distortion measured in voltage and current at the loudspeaker terminals reveals the loudspeaker nonlinearities in the motor and suspension system. For example, an offset in the voice coil rest position can be detected in the asymmetry (e.g., shift to the right sight) of the bell shaped force factor characteristic as illustrated in Fig. 13.

线性系统的鉴定在扬声器测试领域已有很久的历史，可基于集总参数模型通过匹配电阻抗预估值至实测值来实现。对自由模型参数最好的评估方法是 Thiele/Small（T/S）参数，如图 9 左下角截图所示。这些参数包括音圈电阻，谐振频率，Q 值等，便于诠释。但是线性模型局限于小信号领

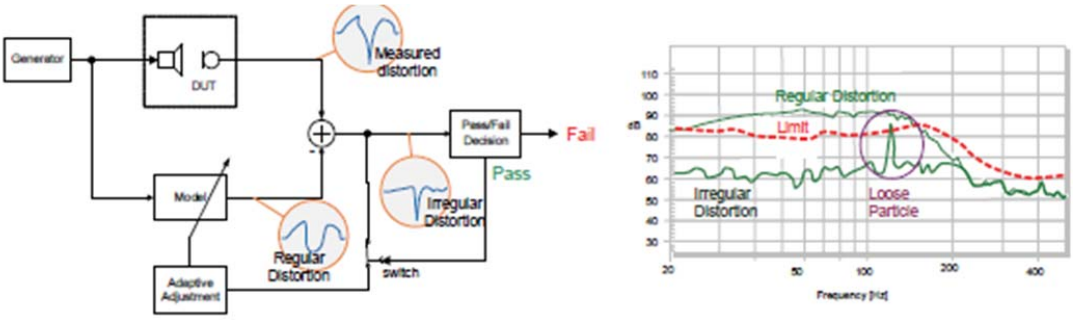
域，不能用于解释大信号状态下高频区域失真的产生。非线性系统鉴定通过测量扬声器两端的电压和电流值来测得非线性失真，反映扬声器驱动系统和悬挂系统的非线性。例如，通过力系数特性钟形曲线的非对称性，可诊断音圈静态位置的偏位量，如图 13 所示。



图示 13：测量扬声器两端的电压和电流值以确定力系数的非线性，从而测出音圈偏位量

A model with identified parameters also provides the state variables (e.g., displacement, voice coil temperature) for an arbitrary stimulus and dispenses with an additional sensor (e.g., laser). System identification can also be used for the measurement of irregular distortions (e.g., caused by a small loose particle) which are masked by regular distortion (e.g., caused by motor and suspension) and not detectable by a human ear or conventional signal and system analysis. Such a defective unit cannot be shipped to the customer because the defect may become worse in the final application (e.g., particle causes voice coil rubbing) eventually generating audible distortion. An adaptive model is used to learn the deterministic properties of the functional devices and synthesize the regular distortion which is subtracted from the measured signal as shown in Fig. 14. Such an active compensation (Irrgang, 2006) increases the sensitivity for irregular distortion by 10 – 30 dB and belongs to the technologies which outperform the capabilities of a human tester.

如果模型参数已知，便可从中获得状态变量（如位移和音圈温度），不论使用何种激励信号。这就不必再使用额外的感应器了（如激光头）。检测被规则（如由驱动和悬挂系统所造成）失真所掩蔽的不规则（如微小游离颗粒所造成的）失真时，同样需要系统的鉴定。这样的失真很难被人耳感知，也难以用传统的信号系统分析测得。这种不良扬声器单体是不可用来出货的，因为其缺陷在最终使用中可能变得更加糟糕（如游离颗粒可能导致擦圈），渐渐产生可闻失真。这里我们使用一种更具适应性的系统，结合良品单体特性，在测得信号中减除确定性失真，如图 14 所示。这种主动补偿可将不规则失真的感知灵敏度提高 10-30dB，其性能远远超过听音测试员。



图示14：基于良品扬声器单体的确定性失真特征做主动补偿，更灵敏的检测被规则失真所掩蔽的缺陷。

4.4 Feature reduction

The previous discussion focused on analysis techniques for increasing the sensitivity of the measurement instrument to ensure reliable detection of all potential defects in the device under test. However, features which are not relevant, redundant or having low diagnostic value should be excluded from the following classification to keep the data size small and the processing fast and robust. Table 4 provides an overview of the most important techniques for reducing the dimensions of the feature space.

前面主要是集中讨论了如何提高测试系统的灵敏度以确保能够可靠地把被测试产品的所有潜在不良现象都检测出来的分析方法。然而，对于一些没用的或者重复的以及一些对诊断问题作用不大的特征数据我们应该利用下面的分类方法把它门筛选出来以确保测试数据精确有效。表4 列出了几种主要的特征数据筛选技术。

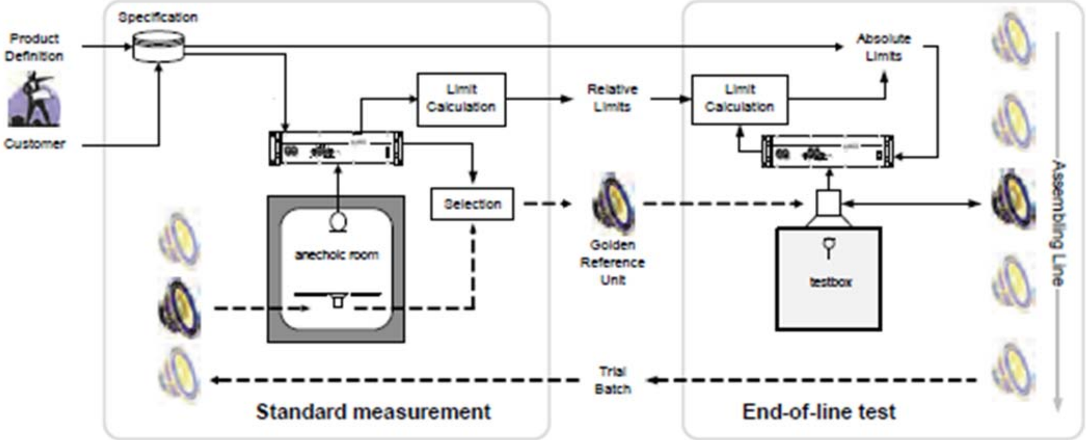
转换方法	实现方法和作用
相对化	通过把测试获得的数据或曲线（如：失真的绝对值）与参考数据或曲线（例如：总声压值）相对比以获得相对量（如：按百分比记的失真）。
曲线平滑和数据抽样	都是最简单的降低曲线解析度的方法。对于基本的声压频响曲线在一定的带宽内（如 1/3 倍频程）取其平均值更有效，而对于高阶失真曲线则是选取指定带宽内的峰值既数据抽样更方便。
正交化	利用主成份分析法（PCA）把一组可能相关的特征数据转换成独立的特征数据。通常主成份数据量会小于或则等于原始数据量，通过把主成份数据进行排序来减小数据的变异量。这种转换对于一维曲线（如：SPL 曲线）和二维数据比较有效（如：通过傅立叶转换得到的时间-频率曲线）
可感知特性的预测	是一种把通过客观的测试得到的物理特性转换成可感知的特征描述来表述工作人员/客户的主观感受的方法（如：失真的可闻度）（ITU2001）。

表4　减少过程分析数据的方法

5. Classification

After providing a set of relevant features from physical measurement, the next step is the generation of Pass/Fail verdicts and the identification of the physical cause of the defect.

在通过物理测量得到一系列相关的特征数据后，下一步就是要判断测试样品的合格与否以及对不良现象进行物理分析。



图表 15：把在标准测试条件下（消音房）定义的检测规格转换成可在特定生产环境（测试箱子）下应用的规格的过程图

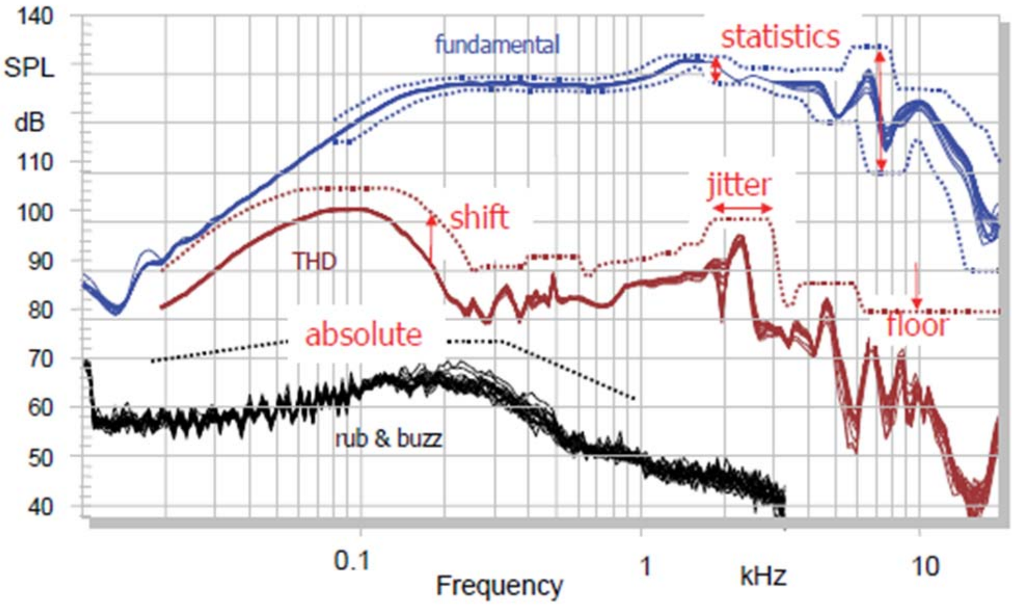
5.1 Pass/fail decision

Faulty units can be easily separated from functional units by comparing the measured variables with specification limits. Those limits correspond with either the target performance at the beginning of the product development, the quality found at the first prototype or the requirement defined by the customer. Specification limits referring to standard measurement condition cannot be applied to end-of-line testing if the measurement conditions are different there. For example, most loudspeaker standards define the sound pressure output at 1 m distance from the drive unit operated in a baffle under free field condition. The test box as shown in Fig. 6 is smaller, less expensive and more convenient than an anechoic room, but requires a transformation of the specification limits.

我们可以通过对测试变量是否符合指定的规格标准的判断就很容易的把不合格品筛选出来。这个测试规格可以是以在开发阶段的样品为基准的到的规格也可以是客户的制定规格。但是由于环境的差异比较大，这种在标准测试环境下得到的测试规格是不能直接适用于生产线的。例如：大部分喇叭的灵敏度的定义都是在自由环境（消音防）的障板中一米距离的条件下测试得到的，但是出于成本和效率的考虑我们的生产线是用一个相对较小的测试箱（表6）来进行测试的，这种情况下我们就要对测试的规格标准进行转换。

This problem can be solved by selecting a limited number of units (usually 10 - 100) and performing a measurement under standard conditions as illustrated in Fig. 15. The functional units which fulfill the specifications are subject to a statistical analysis. After calculating the mean value and variance of all features, *Golden Reference Units* are selected which represent the ensemble best. Some of the absolute specification limits corresponding to standard measurement conditions are replaced by relative limits. Now a Golden Reference Unit and the corresponding relative limits are transferred to the assembly line and measured under non-conformal conditions (e.g., test box). Finally the relative limits are transformed into absolute limits used for end-of-line testing.

按照图15的方法，通过选取一定数量样品（通常10-100个）先在标准的环境下进行测试，然后把测试得到的所有良品取出来进行统计分析。在得到所有特征数据的平均值和测试变化范围后我们就可以把最接近平均值的样品作为标准件，有了这个标准件为基准我们就可以把在标准测试环境下定义的绝对测试规格转换成适用于生产线上的相对的测试规格（相对于标准件）。于是我们就完成了把在标准环境下的测试规格转换成了可以在生产线上进行测试的规格了。



图示16 ：从参考单元统计得到测试规格的计算法

The Golden Reference Unit is stored under manufacturing conditions and can be used to recalibrate the absolute limits at any time when temperature or humidity changes the behavior of the device under test. This limit calculation process must also consider systematic differences between the just assembled unit where the properties are still varying (e.g., drying adhesive) and the Golden Reference Unit manufactured some time ago.

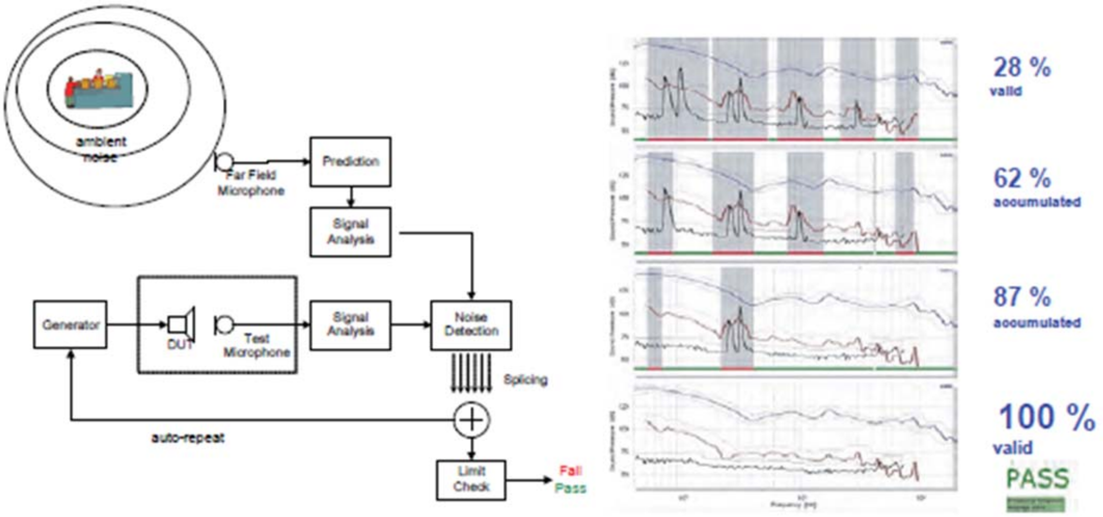
参考单元应当储存在于生产条件相同的环境中以便当测试环境的温度或则湿度发生改变时我门可以随时取出来进行测试系统的矫正 。在计算规格的时候还应同时考虑到新生产的单元的各种系统参数还处于一个不稳定的状态（例如：胶水还没干透）而参考单元已经生产了一段时间并且状态稳定这两者之间存在的差别。

Special algorithms are useful to transfer or generate the specification limits. The shift algorithm is a simple way to generate upper and lower specification limits having a defined distance to the mean value as shown in Fig. 16. If meaningful shifting values are not known, the width of the permissible corridor can be calculated from the variance of the measured variable. For example the upper and lower limits of the fundamental SPL curve in Fig. 16 correspond to ±3 sigma and make the corridor wider at higher frequencies where the variance of the measured variable rises. The floor algorithm is a useful constraint which keeps the specification limit above a threshold. This is, for example, useful for total harmonic distortions which are acceptable if they are smaller than a defined level. A jitter algorithm increases the tolerances in the horizontal direction to cope with sharp peak and dips having a varying resonance frequency.

某些特殊的算法对于转换这些规格很有帮助，如图16的偏移算法是一种简单有效的用于计算规格上下限范围的方法。如果理论上的偏移量不可知，上下限范围的宽度则可以由测量参数的变化范围来确定。例如图16那样，频响曲线的基本频率段的上下限范围正好符合+/-3 Sigma 而在高频段则需要根据实际测试的变化而适当放宽范围。基层算法则是一种能够确保上下限范围大于特定极限的有效工具，例如在判断总谐波失真是否在可接受范围内的时候这种算法就很有用。一种跳跃算法(Jitter)则可以应用在单元的某谐振点位置不稳定的附近以放宽其水平方向的公差范围来控制其频响的峰谷范围。

Statistical algorithms for limit definition have the benefit that only few setup parameters (e.g., shift value) have to be defined which are valid for similar kinds of products. The distance between the measured variable and the upper and lower specification limits may be used as a quantitative measure for grading the quality of the device under test and for assigning the device to a particular quality class.

这些统计法的好处是只需要定义少数个参数（例如：偏移量）就可以应用到各种相似的产品 中。从中得到的测量变化范围和上下限同时也可以用来作为产品的等级划分或者品质分类的依据。



图示17 ：一种能够同时去除无用的生产噪音信号并且能从重复的测试中分离出有用信息的系统

5.2 Detection of invalid measurements

A disturbance from an external source corrupting the monitored signal may invalidate the measurement. Acoustical measurements are especially prone to ambient noise generated in a production environment. A multiple sensor system such as a microphone array can be used for deriving the position of the source and to separate the test signal from the noise. If the test microphone is located in the near field of the loudspeaker as shown in Fig. 17 and a second microphone is located in the far field at some distance from the test microphone, an acoustical disturbance can be detected reliably. The grey sections in the SPL frequency response in the right-hand side of Fig. 17 show the corrupted parts of the measurement.

来自外部的干扰信号会破坏测试系统的准确性。特别是对于声学测试系统,这种来自生产环境的噪音更为严重。不过我们可以通过一种由麦克风阵列组成的多路测试系统来区分出这些来自外部的干扰信号以达到净化测试数据的目的。如果一个测试麦克风放在被测试单元的近场位置同时再摆放一个麦克风在远场位置(如图17)那么我们就可以很可靠地分辨出任何一个声源的位置。图标17右边的灰色部分显示了一些被干扰了的测试数据,想要从这些被干扰了的测试结果中分离出有用的数据的话需要进行多次重复的测试,因为干扰信号通常是不稳定的,通过这种重复的测试就可以有效地分辨并剔除无用的数据然后分离出有用的恒定数据。这种重复测试并分离出有用数据的方法就是实现快速和对测试环境无要求的测试系统的根本所在。

Invalid results require a repetition of the measurement, but it is beneficial to store uncorrupted parts of each measurement and to merge those parts with valid parts of the following repetitions resulting in complete valid set of data eventually. This auto-repeat and splicing technique is an important element of ultra-fast testing providing immunity against random production noise.

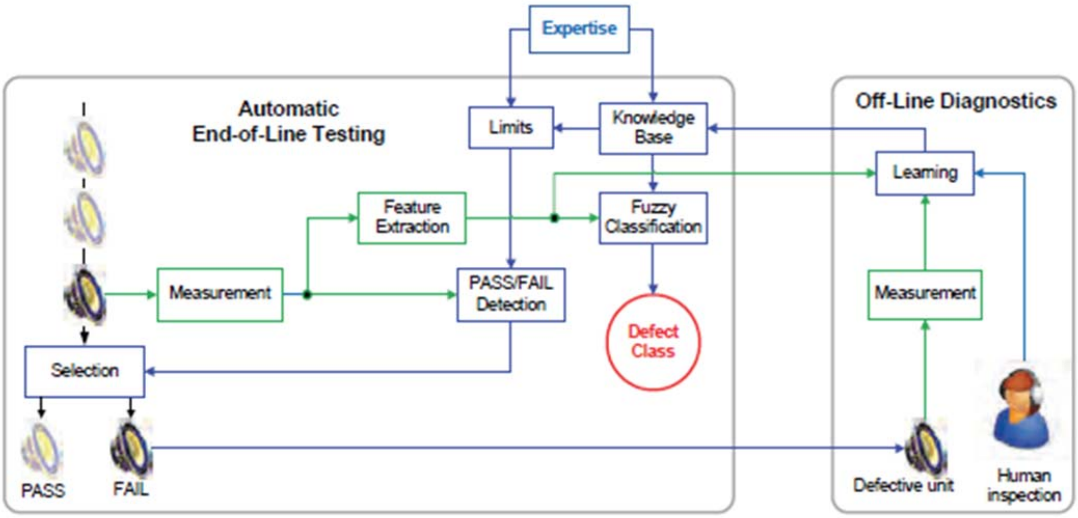


图18 从离线人工诊断数据中自动分类不良数据的过程图

5.3 Defect classification

If a device fails permissible specification limits, it is crucial to identify the physical cause of the defect as fast as possible to ensure timely control of the production process and to maintain a low rejection rate. To accomplish this task, an experienced operator or engineer from manufacturing or product design can perform additional measurements, visual inspection, destructive analysis or other kinds of off-line diagnostics as shown in Fig. 18. For loudspeaker evaluation, new auralization techniques are also useful, providing more sensitivity for defects than normal listening tests. Signal processing can enhance critical distortion components while protecting the operator’s ears against the fundamental component‘s high sound pressure. However, those tools cannot replace the expertise the human investigator has accumulated over time and cannot be transferred to other co-workers.

若待测物没有通过设置的容许公差，则此时能尽快找出原因从而确保及时加强生产控制以维持较低的不良率是至关重要的。为了能实现这一点，最好能有一个富有经验的作业员或制造，设计工程师进行一些额外的测量，目测，解体分析，或者一些如如图 18 所示的其它离线诊断分析。对于扬声器的评估，诊听技术是非常有帮助的，相对于传统的听音测试它更灵敏。相对于高声压的基波成分，通过对信号的处理可以加强失真成分从而保护测试员的听力。然而，这些工具都无法替代人工检测，尤其是随着时间积累下来的听音能力，它也无法转换为其它协同工作模式。

A new objective of end-of-line testing is combining the results of objective testing with the background information about the physical nature of the defect. The first step in this process is the creation of a class, assigning it a meaningful name and storing all relevant information (symptoms, causes, remedies) in a knowledge base. Generic defect classes (e.g., “electrical shortcut”) are already provided by the measurement instrument, but the particular defect classes are generated during the design process and permanently extended during manufacturing. The classificator in Fig. 18 uses this information to determine defect classes which correspond to the measured features at the highest likelihood. Fuzzy logic (Zadeh, 1987) can be used to combine the measured features with non-numeric linguistic variables such as “loudspeaker sounds distorted” and determine the membership of the defect classes. The output of the classification process is not only the name and probability value of the most likely defect class, but also a list of alternative classes at a lower rank. This information is not a strict assignment, but more a guided search process for the operator to determine the most likely defect class.

一种新的客观测量方法集成到该测试中，它通过测量背景噪声来确定是否为不良品。该流程的第一步是创建分类，给每个分类指定一个富有意义的名称，同时在数据库中储存所有相关信息（症状，原因，改良方法）。测量系统已经提供了一些常见的不良品分类，但是一些特殊的缺陷需要在设计过程中补充，或者在以后的生产过程中扩展进去。图 18 中分类使用了该方法根据测试结果来判断不良品的最大可能性并进行了分类。模糊逻辑(Zadeh, 91987)可将测量特性与非量化的语言描述差异综合起来；例如“扬声器听起来失真”并决定了其不良品分类。不良品分类处理时不仅包含了名称，不良品最大可能性的值，同时也包含了其它可能性较小的可选分类。这些信息的定义不是绝对的，但它却为作业员判定其为最可能为哪种不良品提供了很大的帮助。

The verification of the proposed or assumed defect is part of the off-line diagnostics, usually performed on a separate measurement platform. The result of the human inspection is the most important input for the automatic learning process. The measured features of the defective device are used to update the properties of the defect prototype which represents an existing defect class. If the membership function of all existing classes is low or the QC operator detects a failure not known before, there is the opportunity to create a new defect class where the defective unit is identical to the prototype. An administrator who is usually the line leader or an experienced QC engineer supervises feedback of the operator and can unify two defect classes and may improve the verbal description of the defect. The expert system is a valuable tool for accumulating knowledge to train new, inexperienced coworkers and to simplify the communication between team members.

对于先前假定的不良品的确认是线下诊断非工作的一部分，通常采取在单独的测量平台上执行一些其它测量。相对于先前的自动化测量，此时人工检查的结果信息是最重要的。不良品的此时测量特性可用来更新先前的不良品属性信息。如果现有的分类未包含该分类，或者 QC 测试员判断错误或无法判断该缺陷，此时则是一个很好的机会在数据库去创建该缺陷的新分类。通产生产线主观或 QC 工程师可以将该信息反馈给测试员，对两种不良的进行归类，以及改进缺陷的口头描述。专家系统是一种很有价值的工具，它可以用来培训新员工以及没有经验的工人，同时使得不同部门之间的交流更加简化和标准化。

6. Quality monitoring and process control

Although the detection of defect units is the basic objective of end-of-line testing, the properties of the functional units passing the test also provide valuable information about the stability of the production process. Statistical analysis applied to this data reveals drifts and trends early enough to readjust the process before faulty products are produced.

尽管不良品的检测只是产线终端测试的基本测试之一，但是它也为那些良品的状况提供了有用的信息，例如生产线制程的稳定性。对该数据进行统计分析可以在早期观察到生产的偏移趋势，以便早期及时纠正制程从而避免不良品。

6.1 Statistical analysis

The first step of quality monitoring and process control is the calculation of basic statistical characteristics of the measured variables (e.g., resistance) and classification results (e.g., counts of defects) as summarized in Table 5.

品质监控的第一步是对测量偏差（例如，电阻）进行一些基本的统计分析和结果分类（例如，不良品个数），如表 5 所示。

基本特征量	描述及应用
柱状图	通过计算数列中大小相同，不重叠的数据区间上的数目来显示变量的分布情况。标准的柱状图估算了可能的密度函数，并揭示了一些重要的分布特性（中心值，分布，斜率，离散性 以及多种方式）。
算术平均值	各变量数据点的测量值xi之和与变量个数N的商。
中间值	对应于将所有数据按大小排列时居于中心位置的数值。中心值描述了数据偏离的趋势，它比算术平均值更有用，同时抑制了异常值的影响。
指数加权移动平均值(EWMA)	对测量数据序列进行平滑，以降低旧数据的权值。EWMA用于控制表中，通过与各自组计算出的平均值对比以检测较小的偏移和趋势。
标准样品	方差σ描述了各单个测量值Xi的离散性。将子组中最大值与最小值之差即为极差R值。
极差	子组数据中最大值与最小值之差
不良率(RR)	不良率为不良品占总产品的百分比。它是制程合格率的余数。
百万产品中不良品数(DPMO)	它等于缺陷产品（或不良品）占总数的比例乘以单个产品中可能缺陷的数目。

表5：生产线终端测试所需用到的基本统计参数

The calculation of those basic characteristics does not require much processing power and can be accomplished by the computer used as part of the end-of-line tester. This provides an additional benefit as warning and alarm signals can be generated automatically and used as feedback at the end of assembly line.

上述基本特性的计算并不需要太多的处理，它可以作为扬声器产线终端测试的一部分，通过计算机来完成。它的额外好处是能够监视生产情况并对生产异常自动报警。

6.2 Process stability

Statistical process control (SPC) separates variations arising from common causes typical to a particular production process (e.g., manual soldering of wires) from unanticipated, special causes (e.g., a new batch of parts with different properties is assembled). Common-cause variations are stable and predictable while special-cause variations have an atypical pattern and are unpredictable, even from a probabilistic point of view, and may require action to stabilize and adjust the process.

统计制程控制(SPC)将某个特殊的产品制程中的常见问题（例如导线的人工焊接）与不曾预料的，特殊问题（组装了不同特性的新部件）隔离开来。那些常见的问题通常是稳定并且可预测的；而特殊问题通常呈现不同的特征，是无法预测的；即使是可能会预见，也需要采取一些行动来使之稳定，同时调整制程。

The Control Chart is a powerful tool for separating common and special causes. The chart displays the quality characteristic versus time or sample number in comparison with two horizontal lines, the upper control limit (UCL) and the lower control limit (LCL). A centre line between the UCL and LCL curves describes the long-term mean value of the process under control. There are many types of charts applicable to variables (e.g., individual data point of the measured feature, mean value, range) or attributes (e.g., counts of nonconforming units, proportions) of different subgroup sizes based on different statistical assumptions (e.g., underlying distribution) and performance (e.g., sensitivity for shifts). Table 6 describes some of the important charts (further details see Montgomery, 2005).

控制图是一个功能强大的，可用于分离常见问题和特殊问题的工具。该表通过与管控上限(UCL)和下限(LCL)比较来显示品质特性。位于上限和下限之间的中心线描述了制程控制下的长期平均值。这里有几种不同类型的图表用来描述变量（例如：单个测量值，平均值，差值）或者潜在分布（例如:不良品数量，百分比）以及性能情况（例如：偏移的灵敏度）。

图 6 是一些常见的重要图表。（更详细的内容可参考 Montgomery, 2005）

控制图	**定义及应用**
x and σ Chart “X-Bar and S Chart”	包含一对图，用来监控短期平均值及根据常规采样子组里相对大数量（n>10）的标准方差。该图表对偏移监测的敏感度大于1.5σ。
x and R Chart “X-Bar and R Chart”	包含一对图，用来监控短期平均值及相对小数量（n<10）子组数据里的最大偏差（极差）该图表对偏移监测的敏感度大于1.5σ。
EMWA Control Chart	使用指数加权移动平均值来监测较小的由于一些特殊原因引起的偏差（0.5σ到1.5σ之间），这些原因可以通过x或者标准控制图以别的方式指派给常见的原因。在不增加失误的机会下来提高了偏差及趋势的灵敏度。
P Chart	一种根据良品/不良品结果数据生成的不良品占总产品数的比率（比例）图。

表6：用于制程稳定性评估的控制图

Comparing the quality characteristic (variables and attributes) with the upper and lower control limits derived from the long term mean value and variability of the process can reveal a critical “out of control” status. Other rules (WECO, 1956; Nelson, 1984) consider additional zones at lower variance and are more sensitive to small shifts and trends.

According to the WECO rules, a process is “out of control” if one of the following occurs:

- a single point is outside the ±3σ range,
- two out of three successive data points are beyond the ±2σ range,
- four out of five successive points are beyond ±1σ range or
- eight successive points are on one side of the centre line.

通过将品质指标（变量和分布）与管控的上限及下限比较可得到长期平均值和离散型，从而揭示临界的“失控”状态。一些其它的标准（WECO, 1956; Nelson, 1984）考虑了一些较小离散性，同时比小的偏移及趋势会更敏感的其它区域。

根据 WECO 标准，当发生以下情形之一时即可认为制程“失控”：

- 单个数据点位于±3σ 范围以外；
- 2/3 的连续数据点超出±2σ 范围以外；
- 4/5 的连续数据点超出±1σ 范围以外；
- 8 个连续数据点位于中心线的一侧。

6.3 Process capability

If the production process is stable, it is possible to predict the output of the process by using dedicated characteristics as listed in Table. 7.

如果生产制程是稳定的，则我们就可能通过一些特定的特征值（如表7所示）来预测制程的输出。

特征量	定义及应用
制程能力指数（Cpk）	通过估算的平均值μ以及个测量变量值的标准方差σ评估制程能力，假设个变量均在规格上限USL和下限LSL范围内。Montgomery (2005)推荐了一个最小的Cpk：对于现有的制程，建议Cpk为1.33；对于新制程，采用双边规格，建议Cpk为1.50。
制程性能指数（Ppk）	其计算方式与 Cpk 相似，但可应用于那些不稳定还没完全受控的制程中。它不仅仅考虑了常见的情况，也考虑了制程中那些由于偏移和漂移造成偏差的特殊情况。

表7：用于评估制程性能的特征量

The yield of the production process corresponds to the process capability index Cpk, if the process is normal distributed and stable. For example a Cpk=1.33 gives a process yield of 99.99 %. To keep the rejection rate below 3 defects per million opportunities (Six sigma) the short term Cpk should be larger than 2. A first estimate can be achieved by using a few data points (> 17) but the prediction becomes more precise by using long-term estimates of μ and σ based on a larger number of observations.

如果制程是正态分布且稳定的，则产品的合格率与制程能力指数是对应的； 例如：Cpk＝1.33 时，可获得 99.99%的合格率。为了保持每百万个产品中的不良品数目小于 3 个（6 Sigma），则短期 CPk 值应大于 2。对于首次评估，可选用较少的数据（大于 17 个）；但是为了作出更精确的预测，则应通过大量数据对 σ 进行长期评估。

6.4 Process adjustment

The control charts and the indices of process capability reveal one or more problems somewhere at the assembly line which require immediate actions to prevent an increase of the rejection rate. If the relationship between symptom and physical cause is not known, a solution for the problem can be searched by a trial and error method. The success of this approach depends on the intuition and experience of the investigator. A more systematic approach is the fault analysis techniques as listed in Table 8 collecting information on potential problems and optimal remedies.

控制表及制程能力指数能够揭示一个或多个生产专配线中的问题，这些问题需要采取及时行动以避免不良率上升。如果这些问题的症状和本质原因之间的关系是未知的，则可通过反复试验的方法来找出问题的解决办法。该方法的成功与否通常取决于检查人员的直觉与经验。更系统的方式是失效分析技术，如图 8 所示，它综合了潜在问题与最佳补救方法。

The ability to act as quickly as possible when the process becomes instable and incapable is vital. The continuous improvement process (CIP) and the failure mode and effects analysis (FMEA) are examples of evolutionary methods for accumulating knowledge before a potential failure occurs. Because of practical experiences during the development of the product, the expertise of the R&D engineers is an important source. This information has to be documented in a format (e.g., fishbone diagram) and language suitable for application at the assembly line. If the manufacturing is outsourced to a contract manufacturer, this knowhow will be transferred only if both companies are interested in a close and long-term relationship.

当制程变得不稳定和不可靠时，能及时发现问题并采取行动的能力是至关重要的。在潜在失效模式发生之前，可通过制程持续改进（CIP），失效模式及影响分析（FMEA）等评估方法来累积信

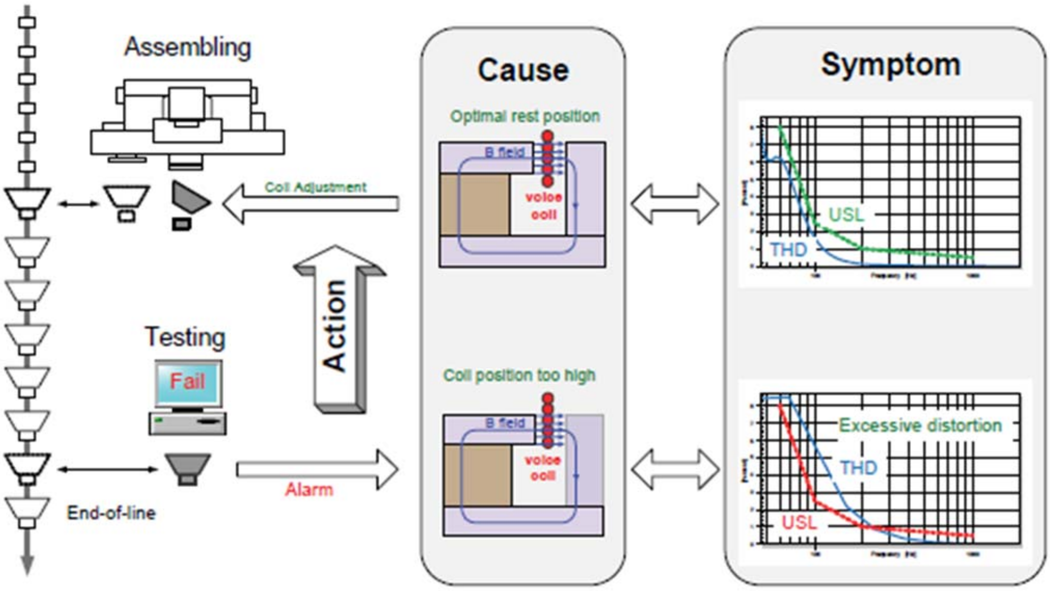
息。在新产品开发阶段，研发工程师等专家的意见是非常重要的。这些信息可以以文档（如：鱼骨图）或者其它文字的形式应用到生产装配线上。如果制造商是从其它外部供应商处采购部件，同时双方对长期的合作保持紧密关系，则同样可将该方法转让给对方。

New measurement techniques exploiting physical modelling of the device under test and system identification make the relationship between symptoms, causes and remedies more transparent. For example, Fig. 19 shows the adjustment of the rest position of the voice coil in loudspeaker manufacturing. The rest position of the voice coil depends on mechanical suspension which is made out of impregnated fabric, rubber, foam and other material having varying properties. An offset from the optimal rest position may cause signal distortion which impairs the perceived sound quality. However, the measurement of the total harmonic distortion (THD) is only a symptom and is less suitable for process control. Nonlinear identification techniques as discussed in Fig. 13 reveal the voice coil position and provide a quantitative value (in mm) for the adjustment of the voice coil position. The detection of a voice coil offset and a proper readjustment can be realized as continuous feedback control in automated assembly lines used for micro-speakers in telecommunication applications.

新的测量技术采用物理模型，对待测物进行辨别，使得生产过程中问题症状，原因及补救方法三者之间的关系变得更一目了然。如图 19 展示了某扬声器制造商音圈调整的过程。音圈的平衡位置取决于机械悬挂系统，它通常用浸透的的织物，，橡胶以及各种不同属性的材料制造。音圈最佳定位位置的偏移可能会造成失真，从而降低音质。然而，通过测量总谐波失真（THD）仅能发现一些症状，但它对生产制程管控并不是很有效的。在图 13 中讨论到的非线性识别技术能够发现音圈定位问题，并且提供了调整音圈位置一个量化值（单位为 mm）。这种音圈位置偏移的侦测以及进行适当调整的方法可以以通讯的方式实时地反馈给自动化转配线。

方法	描述及应用
失效模式及影响分析 （FMEA）	一种归纳法，它通过收集类似产品的经验和工程知识， 通过定义原因，影响及采取的措施以及对严重度，可能度和可检测度打分来确定产品以后可能潜在的失效模式。（Kmenta& Koshuke, 2004）
根本原因分析法 （RCA）	与应付表面现象相反，该方法试图找出，纠正问题的根本原因。
故障树分析法 （Fault Tree Analysis）	一种推论法，它使用布尔逻辑（与，或门，（IEC, 2006）），对子系统中的初始故障，外部事件进行逻辑综合，来解释不理想的事件。
鱼骨图 （Fishbone Diagram）	由 Ishikawa 1990 年提出，它收集了主要范畴内的所有原因（例如：人员，材料，方法，环境等等）
因果分析法 （Why-Because Analysis）	一种事后分析法，它用来研究事件相关所有因素之间的因果关系。
Poerto chart	根据客户抱怨或者其它品质问题的发生机率，成本以及频率。该图表通常显示条形图和线图，条形图以递减的方式显示不良品的个体值，线图显示其累积值。(Wilkinson, 2006)
制程持续改进 （CIP）	根据测量系统，统计制程控制，客户，作业员，品质人员以及设计工程师的反馈信息，进行额外的改善。（Imai, 1997）
试验设计 （DOE）	一种通过对试验品运用对比法，随机法，复制法以及其它原理来收集某些受控处理影响的方法。（由 Fisher 于 1971 年提出）

表 8：制程控制中的常见方法



7. Data archiving and reporting

End-of-line testing produces an enormous amount of data. This section discusses alternative ways of storing the results in an effective format to support statistical analysis and the distribution of relevant information to different recipients.

生产线终端测试会生成大量数据。该节讲述了以有效格式来存储数据进行统计分析以及发布数据给相关人员的可选方法。

The results of end-of-line tests reflect the quality of the total production process and are not only interesting for manufacturing, but also for the supplier of parts, design engineers in the R&D department, QC management and customers. However, each group needs a different part of the data. For example, manufacturing should immediately receive all parameters which are the basis for process control; however, those data are less important for the customer who is more interested in the overall quality of the products. The management is usually satisfied with the number of devices tested and the process yield. The designer from the R&D department is more interested in detailed measurement results of defective devices under test to understand the physical cause of the problem and discovering clues for improving design or simplifying manufacturing. The parts supplier (e.g., diaphragms in loudspeakers) only needs parameters (e.g., resonance frequency) which are important for his quality control and to address possible customer complaints. There is usually not enough time during end-of-line testing for isolating this information and generating a separate output file for each recipient in his preferred format. This problem becomes critical if the individual results of all measured devices under test are stored to ensure traceability about every step in the process chain. In this case, each device under test is identified by bar code or printing an individual label for each device under test. The computer associated with the measurement system is only used for writing a short entry for each measured device in the log file (i.e., general information such as serial number, date, time, verdicts, Pass/Fail result and selected important single-valued parameters).

生产线终端测试的结果反映了制造商产品的质量，它不仅仅关注了制造商的制程，同时也关注于材料供应商，研发工程师，品质管理以及客户。但是，不同的人员需要不同的数据。例如：制造商应该快速得到所有的参数，这些数据是制程控制的基础；然而，这些数据对于客户来不是很重要的，它们更关注于产品的总体质量。管理层通常满足于测试的数量和合格率。研发部设计人员

可能对不良品的详细参数更感兴趣，以便弄清楚根本原因，改进设计或者简化生产难度。材料供应商（如扬声器振膜供应商）仅仅需要某些参数（例如：谐振频率），这些参数对于它们的制程控制是非常重要的。通常，在生产线终端测试期间是没有足够的时间来分离这些信息并根绝相关人员的需要来生成独立的文件。如果为了确保数据的可追溯性，将生产个环节中的所有测量数据都保存时，该问题变得很严峻。在这种情况下，各待测品可用条形码来识别或者为其打印一个单独的标签。通过日志文件（例如，常用信息包含序列号，日期，时间，判定结果以及一些选定的重要参数）为各测试品创一个短小条目从而将计算机与各测试品之间关联起来。

In many applications, a digital format (e.g., database) is the only way to transfer a large amount of data (e.g., curves) as quickly as possible to a central computer (e.g., server) where the data is stored temporarily and the output file for each recipient is generated by a separate extraction process. The central storage of the test results allows, for example, matching loudspeaker units with similar acoustical properties which are sold as pairs to the customer.

在许多应用中，通常使用数据格式（例如：数据库）来将大量数据传输到中央计算机（例如：服务器），数据被暂时存储在服务器中，同时通过单独的数据提取处理从而输出各用户所需的报告。中央存储器理可以实现一些功能，例如：可以对具有相同声学特性的扬声器进行配对以便销售。

8. Conclusion

Testing the manufactured device at the end of the assembly line differs significantly from the measurements performed during the development of the product. Most information, graphs, post-processing tools appreciated by an innovative R&D engineer are less useful in manufacturing where an identical replication of the prototype is important. End-of-line testing uses highly specialized test equipment providing limited information sufficient for quality assurance and process control. New sensor, signal analysis and system identification techniques are used to ensure reliable detection of defects at an early stage before the product is shipped or mounted in the final application. Ultra-fast measurement techniques using an optimal stimulus are crucial for comprehensive testing within the available cycle time. End-of-line testing has to cope with measurement conditions which do not comply with R&D standards (e.g., anechoic room) and ensure comparability within the specification limits (e.g., transfer by Golden Reference Units). Invalid measurements caused by unavoidable disturbances in a production environment must be detected and repeated. This leads to new techniques (e.g., noise immunity) increasing the robustness of the test.

制造厂家的生产线终端测试与开发阶段的测试是明显不同的。一个创新的研发工程师崇尚很多信息，曲线图，后期处理，但是这些对于生产过程并不是很有帮助。生产线终端测试通常使用特定的测试设备，它们提供了对品质保证和制程控制虽有限但高效的信息。使用新的传感器，信号分析以及系统识别技术可用来保证产品在出货或被装配到最终成品前早期检测的可靠性。快速测试技术使用了一个最佳的激励信号，它对于在可利用的时间周期内实现全面测试是至关重要的。生产线终端测试不得不面对与研发阶段不同的测试环境（例如：无响室）并确保在测试公差内的可比较性（例如：通常由参考样品转化而来的）。由于环境造成的无效测量必须被检测出来并重复测量。这就需要一种新的技术（例如：环境免疫能力）增强了测试的有效性。

The measured physical variables and counts provided by end-of-line testing are the basis for process control. Trends and shifts must be detected early enough to adjust the process in time and to ensure a stable and capable production process (Six Sigma). Process control requires knowledge about the relationship between causes, symptoms and actions especially at automatic lines with continuous feedback and automatic adjustment of process parameters. One source of this knowledge is physical modeling provided by product development and applied to the particular requirements in manufacturing. A second source is the off-line diagnostic where a human operator investigates defective devices and extends the knowledge base continuously. This new task will replace manual handling and subjective evaluation which cannot meet modern requirement of 100 % testing of the products manufactured by an automated assembly line.

测量的物理偏差和个数是制程控制的基础。趋势及偏移必须早期被诊测出来，以便尽调整制程以及确保稳定和胜任的制程能力（6 Sigma）。制程控制要有能通过自动化流水线持续反馈信息及自动调整制程参数从而了解成因，症状以及采取行动之间关系的知识。该知识的一种来源为物理模型，它由产品开发人员提供，并应用到生产环节的特殊需求中。另外一个的来源为线下的诊断，它由作业员人工去分析调查，并持续地拓展基本功。新的任务将替代人工处理和主观评价。毕竟对于一个自动化的流水线来说，人工处理和主观评价的方法不能满足 100%检测的需求。

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