RF Immunity Testing

a handy guide

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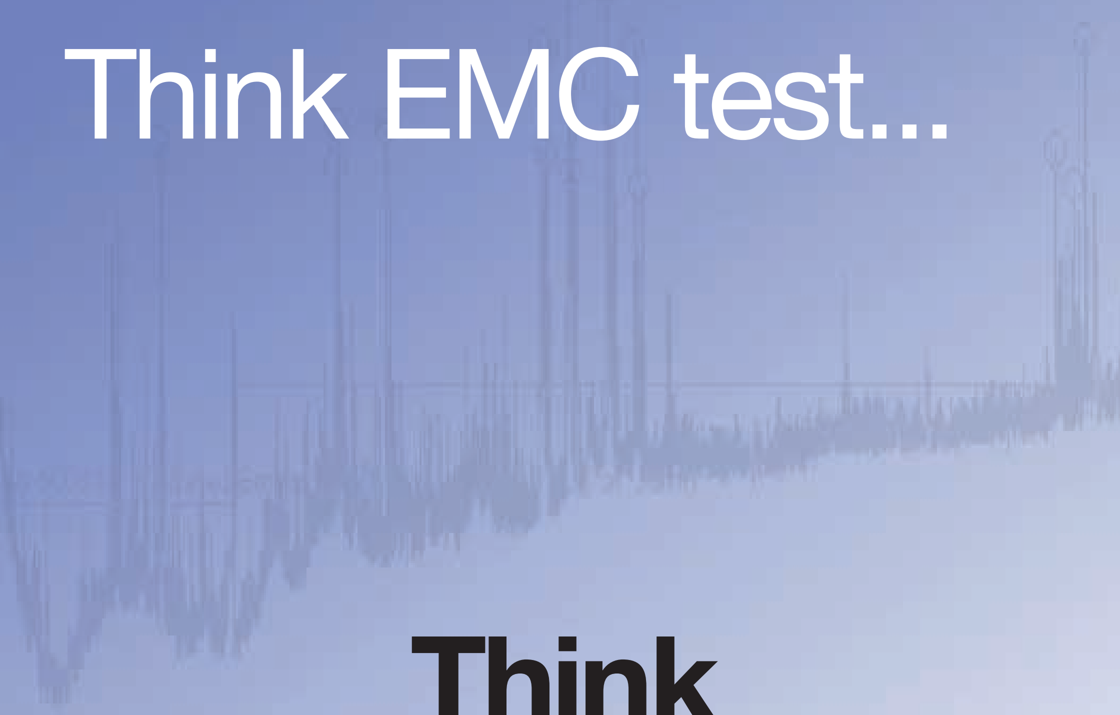

RF Immunity Testing

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The Handy Guide to RF immunity tests

Introduction

The radio frequency (RF) environment is becoming steadily more crowded. Electronic equipment is expected to work alongside portable radio transmitters of many kinds – the ubiquitous GSM mobile phone is only the most obvious example. Any urban location has a profusion of portable radio sources within and around it, and many locations are close enough to fixed transmitters that there are significant field strengths from these sources as well.

A product manufacturer is unlikely to know or have control over the actual location of use of his products, and products should be expected to work correctly in any environment that they are reasonably likely to encounter. Whilst it is a requirement of the EMC and R&TTE Directives that any product placed on the market or taken into service should have adequate immunity, any manufacturer who is concerned about the quality of his products will take steps to ensure this irrespective of the legislation, since the issue is a straightforward one of fitness for purpose.

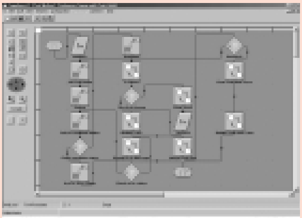
Good EMC design practice will go a long way towards implementing adequate radio frequency immunity, but it cannot ensure it. The purpose of RF immunity testing is to subject a product to a controlled RF stress that represents the likely level of stress that might be seen in its operating environment, over a frequency range which is mostly dictated by practical aspects and experience of real-world problems. The actual response of the equipment is monitored during this test. The choice of these parameters is a compromise between what is possible and realistic to test and design for, given cost constraints, against the degree of certainty of performance that is needed in a probable RFenvironment. The levels and frequency ranges given in international and European standards represent one such compromise; they do not ensure certain immunity in all environments, but give a reasonable probability of adequate immunity in most.

The test methods are divided into application of stress by conducted coupling, and by radiated field coupling. This booklet gives the main features of both these approaches, and starts by looking at the instrumentation needed to perform both of them, before going on to discuss the methods and procedures of each.

EMC Compliance 3 Test Software

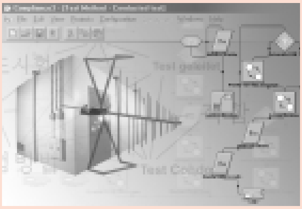
EMC Compliance 3 software has been designed to provide a single platform for all types of RF EMC testing. Its immunity module allows for both simple or complex test configurations to be controlled with ease. In an automatic switched system, there may be more than one signal generator, several amplifiers and multiple transducers. All of these may be configured through a complex arrangement of RF switches.

Not only can the Compliance 3 software draw and display this configuration but it can also test for valid paths and warn against dangerous or incorrect routing of the RF signal. The software will automatically show in the graphical display the RF route for any entered frequency and will also list any frequencies for which no path can be found.



Variable target thresholds

In many cases, particularly automotive and military specifications, the RF stress level to be applied is not constant with frequency. Compliance 3 can create test profiles that can vary linearly of logarithmically with frequency and which can have the acceptance tolerance also varying with frequency. In this way the user can create any test profile simply and easily.



Total Flexibility

Test can be defined that run from the lowest frequency to the highest or reversed to work from the highest to the lowest. If required, the user can specially configure the test to, for example, start at the lowest frequency and run to the first EUT failure point, then run from the highest frequency downwards to the last EUT failure point. The space in between can then be investigated by, for example, running a test at a lower stress level between the failure points. All of this is totally in control of the user and is limited only by the imagination.

Instrumentation and techniques

Generating the RF stress

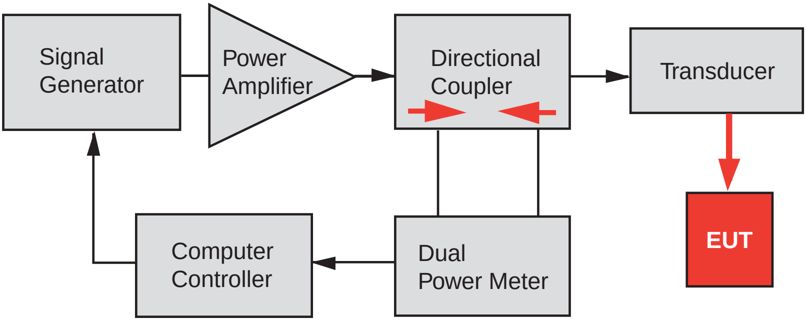


Figure 1 - Instrumentation need for RF immunity

A signal generator is used to supply a power amplifier with an RF signal (at a level of typically less than a milliwatt) of the required frequency and modulation. Good spectral purity is required so that spurious signals are not fed into the power amplifier, which must itself be linear, rugged and capable of the desired output power over the entire frequency range of the test. The amplifier output feeds a transducer which applies the stress to the Equipment Under Test (EUT). The amplifier output power is normally measured by a dual-directional (forward and reverse power) coupler in conjunction with an RF voltmeter or spectrum analyser/measuring receiver. Computer control closes the loop so that scanning the frequency range, applying modulation and selecting the field strength is done automatically and repeatably.

Signal generator

The signal generator must be able to generate signals over the frequency range of the test and be level adjustable over a sufficient dynamic range to allow the system to generate between zero and the required stress. It must be able to return accurately to any given frequency and level and remain there, and to apply any signal modulation required by the test.

Two not-so-obvious requirements are that it must have a good resolution both for frequency and level and that, when switching between frequencies or levels, it must not produce any excessive transient levels. Transients from the signal generator will be amplified by the power amplifier and could damage the transducer, unit under test or even the amplifier itself. Even if the levels are not damaging, such transients are likely to upset the EUT and cause a false indication of susceptibility which is difficult to separate from the phenomena caused by the correct test level.

Level resolution is important because, whilst the signal generator output is set in a logarithmic (dB) manner, the stress is measured in linear units. The linear step sizes in volts at 10V for generators with 0.1, 0.5 and 1dB steps are 0.12V, 0.59V and 1.22V. Clearly, a generator with poor level resolution cannot set the required stress accurately: 0.1dB is the worst resolution that should be accepted.

Power amplifier

Beyond covering the required frequency range and having sufficient power output, an amplifier used in EMC testing must be able to withstand the high VSWR levels which it will inevitably see. Biconical antennas in particular have a high VSWR, and frequent connection and disconnection of the amplifier output cable can lead to damage or incorrect connection which also gives a high VSWR. It's important that the amplifier is not damaged when it sees this condition, however occasionally.

Power Amplifiers

Schaffner offers a wide range of power amplifiers specifically designed for EMC testing with a high degree of tolerance of input loads. All amplifiers are Class A, offering excellent linear power. For radiated measurements some amplifiers have power slewed with frequency to accommodate transmit antennas.

CBA 9413
Power Amplifier

For conducted testing, this reliability is less important because there should be a 6dB attenuator on the output of the amplifier at all times, although if the system can be assembled and disassembled regularly, open and short circuit connections are still a possibility.

The bandwidth of the amplifier, that is the frequency range over which its output power can be maintained, is clearly an important parameter for a given test range. Particularly for the wide range of frequencies for the radiated test (in some cases, 26MHz to 2GHz) you may need several amplifiers with complementary bandwidths to cover the range. This in turn means band switching during the test, which is an undesirable complication.

The gain of the amplifier (output power divided by input power) does not have to be constant over the frequency range, since the signal generator level is constantly being adjusted to maintain the desired stress, as long as it is stable and adequate to allow the system to work at the extremities of the range.

The amplifier has to operate linearly. Non-linearity will cause the modulation envelope to be distorted, and increases the output of the harmonics of the desired signal. The standard specifications call for the harmonic content of the generating system to be kept below -15dB relative to the fundamental.

Amplifiers are considered linear up to the point where the actual output differs from the predicted ideal output by 1dB. This point is usually of the order of 60-75% of the saturated output power.

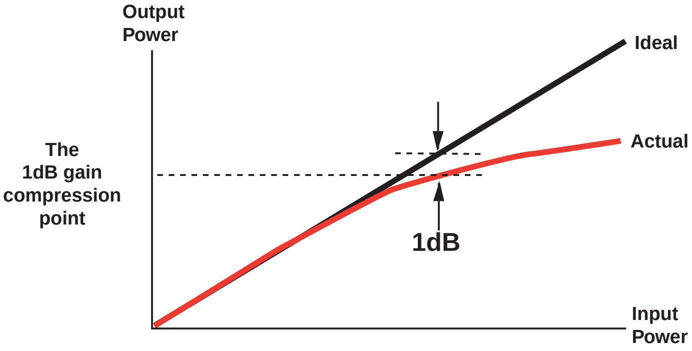


Figure 2 - Power amplifier gain compression

The amplifier's maximum power capability depends on the stress required for the test, and the loss in the transducer that will be used to apply that stress. Later sections discuss these transducers and you will find charts of required power versus stress for each of them.

Modulation

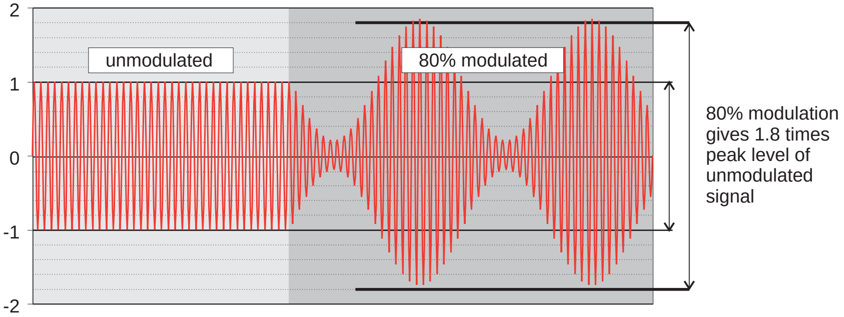
The EUT may be susceptible to modulated RF but not to unmodulated. Signal circuits will detect the RF signal and respond to its amplitude; an unmodulated carrier may cause a non-critical DC shift in AC coupled circuits whereas detected modulation can be within the signal bandwidth. The EUT can also be immune to a high level of RF but unexpectedly susceptible at a lower level.

The IEC 61000-4 standards mandate the use of amplitude modulated (AM) signals. (Using frequency modulated (FM) signals does not generally produce any additional susceptibilities except in special cases.) For AM, a 1kHz sinewave is normally used, with some product-specific exceptions. These standards refer the specified level to the unmodulated signal, which is then modulated at 80% depth. This increases the peak applied signal by over 5dB, as discussed below. By contrast, some automotive RF immunity standards refer the test level to the peak value after modulation.
An alternative modulation technique is pulse modulation, in which the signal is effectively switched on and off. This has been required by ENV 50204 for emulating GSM signals at 900MHz, where a 200Hz pulse modulation is specified. No increase in the overall peak level is caused by this technique. Although this standard is now withdrawn, you may still decide to apply this test specifically to check for immunity to a real-life GSM threat.
In calculating the power level required from an amplifier, you have to take the effects of modulation into account. The 80% modulation depth implies an increase in peak power of 1.8^2 times,

$$= 3.24 \text{ or } 5.1\text{dB}$$

Hence a power of 3.24 times that calculated from the transducer properties is required from the amplifier.

Figure 3 - Modulation



Dwell time and sweep rate

You need to consider carefully the dwell time of the interference; the signal must be applied for a sufficiently long time for the EUT to respond and so should be as long as the longest appropriate EUT time constant. Longer times will be necessary for systems with complex operating cycles. A compromise is often necessary to avoid tests which could otherwise take weeks to complete. The maximum continuous sweep rate allowed in IEC/EN 61000-4-3 and -6 is 1.5×10^{-3} decades per second, which is equivalent to 200 seconds per octave. If as is more usual the frequency range is swept incrementally, the maximum step size allowed is 1% of the actual frequency. These standards require that the dwell time shall be sufficient for the EUT to be exercised and to be able to respond; if you take a step size of 1% and apply it to the sweep rate quoted, the shortest dwell time should be 2.88 seconds. This is arrived at as follows:

For a decade sweep with x being the required number of steps,

$$1.01^x = 10 \text{ or } x = 1/\log(1.01) = 231.4$$

A whole decade must take $10^3 / 1.5 = 666.6$ seconds, so the dwell time t per step is

$$t = 666.66/231.4 = 2.88 \text{ seconds}$$

To this must be added the control settling time between each frequency step, which depends on the software algorithm used to perform the test.

The EUT's frequency dependence can also be due to narrow-band susceptibilities of the circuit operation, e.g. a sampling mechanism clocked at 500kHz may be susceptible at injection frequencies near to this frequency and its harmonics. If the design of the EUT is such that this might occur, then the interference signal must be swept or stepped across the whole specified frequency band at a rate slow enough, or a frequency spacing fine enough, to pick out any narrowband susceptibilities, and special attention must be paid to any known likely susceptible frequencies. The above-mentioned standards take account of this by requiring that sensitive frequencies (e.g. clock frequencies) be analysed separately.

Product standards for radio receivers have special procedures for allowing certain narrowband responses and for allowing an exclusion band around the receiver's own range of frequencies.

Level setting: power meter and directional coupler

Two methods of recording the required power profile versus frequency are possible. In a low cost system, only the power delivered by the signal generator to the amplifier is recorded.

During calibration, at each frequency step the software gradually raises the signal generator level until the sensor reports that the desired stress level has been achieved, and during the test, these generator levels are repeated by the software.

This method relies on the amplifier not to change its performance between the calibration and the test. This will often be an acceptable assumption but there is the risk that the gain will change with temperature, a manual gain control on the amplifier will be moved or that the amplifier will fail completely. There is nothing in the system which would tell the user that this has happened. There is also the problem that the loading on the amplifier output may change when the EUT is placed in the chamber, due to too-close coupling with the antenna. Without monitoring the amplifier output power there is no way of detecting this effect. In fact, IEC/EN 61000-4-3 does not allow this method for a compliant test.

A better approach (and one which is compliant with the standard) is to monitor and record the output from the amplifier. A directional coupler will sample a small amount of the power leaving the amplifier which can be measured with an RF power meter. The software, as before, raises the signal generator output until the required stress level is achieved but in this case the calibration routine also records the power from the coupler. During the test, the signal generator level is set to the expected value and then adjusted until the power previously recorded is re-established. This ensures that the same power is delivered to the transducer regardless of any changes in the amplifier. In fact, power to the transducer flows in both directions – some is reflected back from the transducer. Some tests (automotive and military) also measure the power reflected and record and reset to the difference between the two (net power). This can be achieved using a Dual Directional Coupler and a dual channel power meter. Net power is a more accurate measure of the power actually passed through the transducer to the EUT, but there are practical difficulties at high VSWRs which make the forward power method easier to use, and it is mandated in the IEC-based standards.

Multi-Channel Power Meter

The Schaffner 4 channel power meter is a cost-effective solution, designed to be used in systems. Its levelling characteristics are programmed into the system software.

Conducted RF immunity tests

At frequencies up to the point at which the EUT dimensions approach a quarter wavelength, the major coupling route into the EUT is via interference injected in common mode on the connected cables. Cable testing is therefore an important method for checking RF susceptibility, and IEC/EN 61000-4-6 specifies the test methods. Any method of cable RF injection testing should require that the common mode impedance at the end of the cable remote from the EUT is defined. Each type of cable should have a common mode decoupling network at its far end, to ensure this impedance with respect to the ground reference plane (GRP) and to isolate any ancillary equipment from the effects of the RF current on the cable. For equipment which will be used and tested in a system where the cable lengths and terminations at either end are controlled, then these terminations provide the appropriate common mode impedance. Otherwise, where the far end termination is unspecified, a nominal impedance of 150 ohms will represent the average of most installation conditions, which can vary between a few ohms and a few hundred ohms over the test frequency range of 150kHz up to 80MHz.

If ancillary equipment (AE) is not isolated from the signal by a decoupling network or filter, then it must be able to withstand the applied RF without affecting the system performance.

The CDN family

The most straightforward method of coupling is by a capacitive connection to the cable under test. The disturbance signal is split via a coupling network to each of the conductors in the cable, so that the disturbance appears in common mode on all conductors together.

As well as a coupling network, a decoupling network is required to prevent the signals applied to the EUT from affecting other devices or being fed into the mains power supply. The combination of a series resistance of 100 ohms and the amplifier output impedance of 50 ohms establishes a common-mode RF impedance at the EUT port of 150 ohms. The coupling and decoupling networks are normally combined into one box to form a so-called coupling/decoupling network (CDN).

The power requirements are low compared to other methods of coupling; 7W is normally adequate to give a 10V test level. An attenuator of at least 6dB is placed between the power amplifier and the network to prevent the power amplifier's variable output VSWR from affecting the results. Tests can be carried out from 150kHz to 80MHz or above.

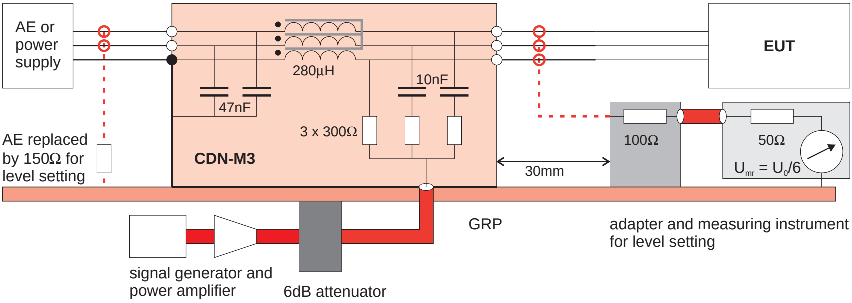


Figure 4 - The coupling/decoupling network: example for 3-line mains

CDNs are available for many applications including screened cables, mains power leads, unscreened pairs and non-balanced pairs, although difficulties exist for some types of unscreened cable, particularly wideband balanced data pairs. The problem is similar to the problem of testing emissions at telecom ports, where the network (in that case described as an Impedance Stabilising Network) must not affect the transmission of the wanted signal. Simplified diagrams of various CDNs are given in IEC/EN 61000-4-6.

CDNs

Schaffner offers one of the widest ranges of CDNs to cover most standards. In addition to the freqeucy published in the standards (150kHz - 80MHz), Schaffner CDNs are extended to the higher frequency of 230MHz.

The EM Clamp

A useful alternative to the CDN for RF injection is the EM-clamp. This device consists of a tube of split ferrite rings of two different grades which can be clamped over the cable to be tested, and it is therefore non invasive and can be used on any cable type. Unlike the similar-looking CISPR absorbing clamp, it provides both inductive and capacitive coupling and can be used down to 150kHz.

The signal is fed in via a single-turn loop which extends the whole length of the clamp and is terminated at each end in an impedance. This creates both a voltage which gives capacitive coupling and a current which gives inductive coupling to the cable. The combination of graded ferrite and capacitive / inductive coupling gives the clamp significant directivity, particularly above 10MHz, so that substantially less signal is applied to the AE end of the cable, and the common mode impedance seen by the EUT is quite close to 150ohms across a large part of the spectrum of the test signal.

As with the CDN, the EM-clamp should be properly bonded to the ground plane to give a repeatable impedance. But also as with the CDN, variations due to cable layout on the AE-side of the test setup, and due to the AE itself, are minimised. The generator (power amplifier) output should be fed via a 6dB attenuator to keep its output VSWR low. Even with this extra attenuation, the coupling loss of the clamp is low enough that it does not require very much more power than a CDN for comparable levels.

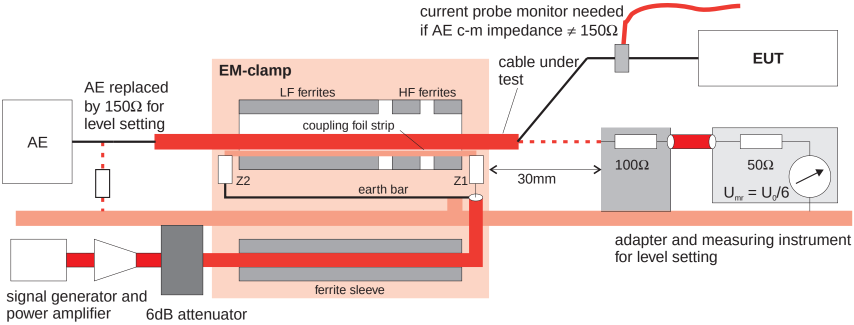
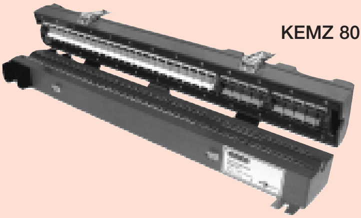


Figure 5 - The EM-Clamp

EM Clamp

The Schaffner KEMZ 801 is rugged and simple to use. Designed to accept input powers up to 100W (150kHz - 230MHz) and 50W (230MHz - 1GHz). It can introduce test levels of up to 100 Volts.



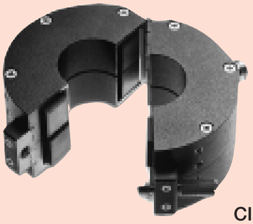
KEMZ 801

The current probe

The current injection probe is another alternative to both the EM-clamp and the CDN. It is less effective than either, but is more convenient to use. The current probe is essentially a clip-on current transformer which can be applied to any cable. It is shielded, and so applies only inductive coupling, without capacitive coupling of the test signal. It has been in common use in military and automotive testing (the “bulk current injection”, BCI test) for many years and has been included in IEC/EN 61000-4-6 since many test laboratories are familiar with it, but this has resulted in some anomalies with respect to setting the injected level.

Current Injection Probe

Schaffner injection probes have a unique method of spring-tensioning their internal cores to improve insertion loss.
This feature also allows field replacement of thermally or mechanically damaged cores.



CIP 9136

A principal disadvantage of the current probe is that it gives no isolation from the ancillary equipment end of the cable, and no control of the cable common mode impedance. The current will flow in the cable according to the ratio of the common mode impedances provided by the EUT and the AE, and at the higher frequencies, according to the cable resonances. The actual stress current applied to the EUT is therefore very variable and also very hard to repeat, because of its dependence on AE and cable impedances. The current probe should only be used if all other methods are either impractical or unavailable.

It is best suited to system-level injection where the AE and cable layout are fixed and known, and the physical limitations make it difficult to apply CDNs or the EM-clamp. A further disadvantage is that because of the higher coupling loss, the power required for a given stress is greater for the current probe than for any other method.

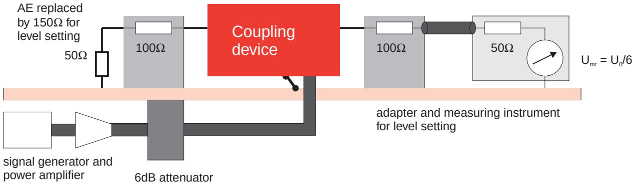
Calibrating the injected level

The test as specified in IEC 61000-4-6 relies on the substitution method of setting the applied level. There are two basic calibration jigs, one for the CDN or EM Clamp and another for the current probe.

The object in both cases is to terminate the transducer in a known impedance and then to measure the stress level applied in that impedance. The power required to give this same stress level is then repeated in the actual test. For the 150 ohms system the required power level must give a reading of $V_{stress}/6$, or (V_{stress} – 15.6dB). For the 50 ohms system it should be $V_{stress}/2$, or (V_{stress} – 6dB). The factor of 2 is needed because the stress voltage is given as an open circuit value, and the factor of 3 in the 150 ohms system is needed because of the effect of the resistive divider.

In both cases, the level can be measured by any RF measuring device, but a point to consider is whether a broadband (power meter or RF volt meter) or a tuned (spectrum analyser) instrument should be used. The disadvantage of a broadband instrument is that it would include harmonics as part of the test level.

Severity levels V_{stress} are specified of 1, 3 or 10V unmodulated open circuit voltage (emf). The actual level to use is given in the appropriate product standard.



Alternative 50Ω level setting for current injection probe

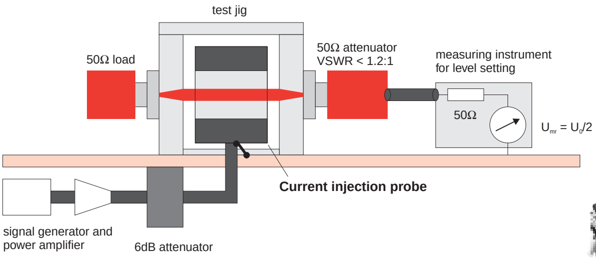
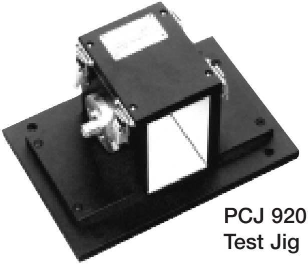


Figure 7 - The Calibration set-up



PCJ 9201 Test Jig

Ground reference plane

The Ground Reference Plane (GRP) is an essential part of the conducted immunity test. *A proper test is impossible without a GRP*. All EUTs, with or without a safety earth connection must be tested over a GRP, since it provides a return path for stray capacitance from the EUT. You should also be aware that the EUT's earth connection itself is tested for immunity to induced RF. The GRP should be:

- at least 0.2m larger than the boundary of the EUT and all coupling devices and ancillary equipment that will be used with it;
- made of copper, aluminium or steel, but the thickness is not too important;
- bonded to the local supply safety earth (this is for safety only, and is not necessary for the measurement);
- bonded by a very short, low-inductive strap to the reference terminals of the CDNs or EM-clamps. A length of wire is not adequate for repeatability at the higher frequencies. The CDN should preferably be bolted directly to the GRP.

Test layout and method

For table-top apparatus the signal is applied via coupling/decoupling networks (CDNs) to cable ports of the EUT. When CDNs are not suitable, the alternative methods of EM-clamp or current injection probe can be used. Cables leaving the EUT in close proximity or in conduit are treated as one cable. EUTs with many ports need only be tested on between 2 and 5 ports, selecting the most sensitive configurations.

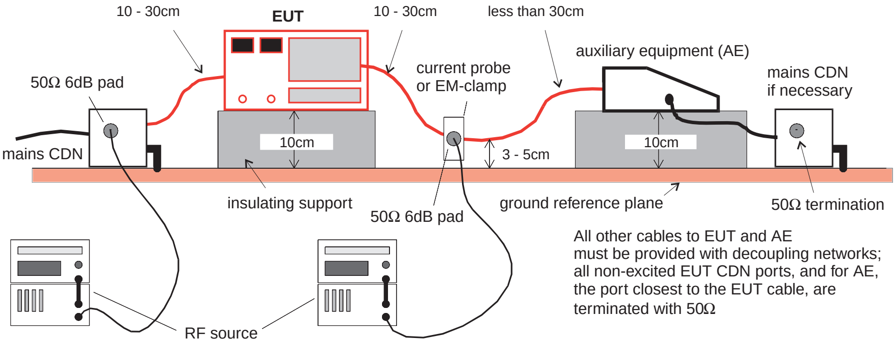


Figure 8 - Conducted Injection Test Layout

The test environment

The test should be well decoupled to prevent any disturbances from affecting other equipment. These can be coupled out of the set-up either via the mains supply or by direct coupling to the leads. Although the CDN will reduce both the noise on its AE port and variations in the cable impedance, it does not do this perfectly, and a permanently installed RF filter at the mains supply to the test environment is advisable. Other cables should either be kept local to the test environment, or filtered to the ground reference plane if they leave it. Ambient radiated signals should also be attenuated and it is usual to perform the measurements inside a screened room, with the floor of the room forming the ground reference plane. However a fully screened room is not essential if other equipment is far enough away for extraneous disturbances to be tolerated.

The equivalent circuit

To understand the conducted immunity test, an equivalent circuit is useful. For a general EUT such an equivalent circuit is shown in Figure 9. The disturbance is applied in common mode with respect to the ground reference plane and therefore generates a current, whose magnitude depends on the EUT's RF common mode impedance at each port, which flows into and through the circuits within the EUT. In these circumstances, "earth" may be either the safety earth connection, or stray capacitance to the GRP. The current within the EUT creates effects at sensitive circuit nodes which then manifest as susceptibilities in the EUT's operation.

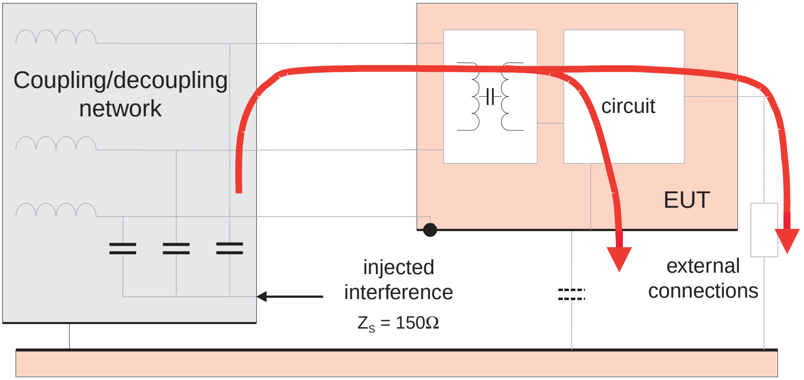


Figure 9 - General Conducted Immunity equivalent circuit

Radiated RF immunity tests

The standard test for radiated immunity is IEC/EN 61000-4-3. This requires a radiated RF field generated by an antenna in a shielded anechoic enclosure using a pre-calibrated field, swept from 80MHz to 1000MHz with a step size not exceeding 1% of fundamental and dwell time sufficient to allow the EUT to respond. The antenna faces each of the four sides of the EUT in each polarization (and top and bottom if these might be affected), hence there are 8 or 12 tests in all. Amendment 1:1998 adds tests from 800-960MHz and 1.4-2GHz for protection against digital mobile phones. Field uniformity as described shortly is required of the chamber.

Annex D allows alternative methods such as a stripline or TEM cell provided that field homogeneity requirements are met and that the EUT and wires can be arranged as specified – which is not always simple to achieve, especially for larger EUTs. Annex H states that the method may be used down to 26MHz.

Severity levels are specified of 1, 3 or 10V/m unmodulated; the actual applied signal is modulated to 80% with a 1kHz sinewave. The standard does not itself specify one particular level for compliance purposes, that is the function of the generic or product standards which refer to it.

Antennas

The antenna is a transducer between the power output of the amplifier and the field in the environment around the EUT. An antenna for RF immunity testing should be able to generate a plane polarised field over the widest possible frequency range (preferably the whole of the required test range, which is nearly two decades) with the best efficiency. The Schaffner BiLog range has evolved to meet this requirement in an optimum fashion.

The applied field strength E can be found from the power fed to the antenna, if no power is reflected, as follows:

$$E\ (\mathrm{V/m}) = \sqrt{(30 \cdot P \cdot g)}/d$$

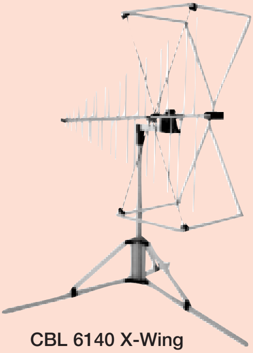
where **P** is the power fed to the antenna
g is the antenna gain
d is the distance from the antenna to the measuring point

The effect of the antenna gain is to concentrate the power into a narrow beam and therefore make the field generating process more efficient. For typical EMC antennas, at low frequencies the antenna becomes inefficient, so that the gain falls and the actual delivered power requirement increases. This equation also shows that the power requirement for a given antenna is dependent on both field strength squared and distance squared. So, if you have an amplifier of a particular power rating, the field strength can be increased by reducing the test distance; but the power required increases rapidly with increasing field strength or distance. Unfortunately there are limits on the minimum test distance that is possible. The standard recommends 3m but allows a distance down to 1m. There are two particular phenomena which dictate as great a distance as possible:

- directional antennas such as log periodic types will illuminate a smaller area at close distances, resulting in an inadequate uniform field area;
- proximity between the antenna and the test object changes the characteristics of the antenna, invalidating the field calibration that is made in the absence of the EUT.

X-Wing BiLog Antennas

X-Wing antennas are a development of the classic BiLog antenna developed by Schaffner. They have been designed specifically for immunity testing in chambers where their folded elements allow low frequency power to be efficiently projected forward without significantly affecting the high frequency performance. At the same time compact size reduces chamber coupling effects.



CBL 6140 X-Wing BiLog Antenna

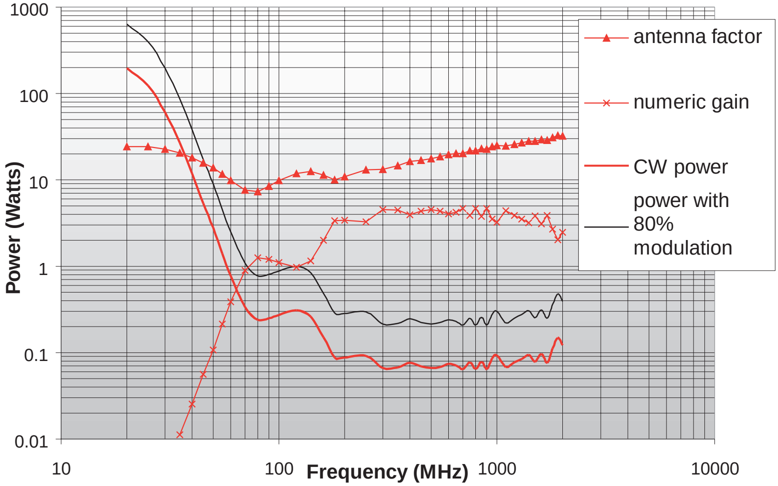


Figure 10 - Drive Power for 1 V/m @ 3m Spacing CBL6141

The power needed for a field strength level of 1V/m at a test distance of 3m is shown versus frequency for the CBL6141 BiLog in Figure 10. For other levels, multiply by the square of the field strength. For a 1m distance, a reduction in power of 9 times is possible. You can see from the graph that the low frequency end requires the greatest drive power, since the antenna is at its least efficient in this range. This graph also shows the increase in drive power necessary to deal with modulated RF, as discussed earlier. Developments in BiLog design have allowed an improvement in low frequency efficiency, allowing either lower power amplifier ratings or an extended low frequency capability.

Using a screened room

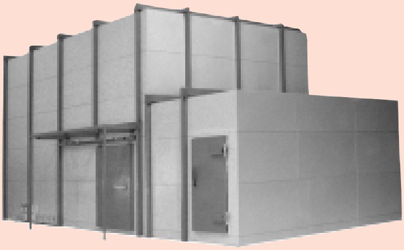
To avoid interference with other radio services you have to use a screened room for the radiated tests. An untreated room though, is almost useless for this purpose. The metallic walls of the room form a highly effective resonating structure whose resonant frequencies are given by the equation

$$\mathbf{F\ (MHz)} \quad = \quad \mathbf{150 \cdot \sqrt{\{(k/l)^2 + (m/w)^2 + (n/h)^2\}}}$$

where **l**, **h** and **w** are the chamber dimensions in metres
k, **m** and **n** are any integer value, but no more than one at a time can be zero

Anechoic chambers

Schaffner offers a range of anechoic chambers (**Impact Series**) which can be user defined to meet varying technical and budgetary specifications. All constructed on site by our expert installation team and optionally calibrated 'on-site' by our UKAS accredited team, these chambers offer a high degree of performance accuracy and quality.



Impact Chamber

So for instance the lowest resonant frequency of a chamber 7.2m x 4.8m x 3.5m occurs with k, m and n equal to 1, 1 and 0, and is at 37.5MHz.

The effect of the resonances is to severely distort the coupling characteristics between the EUT position and the test antenna. The field at any position in the chamber is the vector sum of the fields arriving from all directions, including the direct field from the antenna but also the reflected fields from all six surfaces of the chamber. As a result, the actual field level varies widely at any given position over frequency, as the wavelengths and hence the phases of the reflected signals change; and for the same reason it also varies widely at any given frequency, with position in the chamber. Achieving an adequately uniform field across the desired frequency range and within the space occupied by the EUT under these conditions is impossible.

This means that anechoic absorber material must be applied to each of the internal surfaces of the chamber. The absorber reduces the amplitude of reflected waves to an acceptable level. Two types of absorber are in common use, ferrite tiles and carbon loaded foam. The foam absorber is relatively light and easy to install, but needs to be a significant fraction of a wavelength deep, and so for operation at low frequencies it takes up a large volume within the chamber. Ferrite tiles are thin and do not affect the useable volume, but they are heavy and may require strengthening of the chamber structure, and have a relatively restricted operating bandwidth. A useful compromise for an extended frequency range is to use both types, applying the ferrite optimised for damping at the lower frequency end and a small dimension foam absorber for the higher frequencies.

Field uniformity and level setting

The classical method of setting the field strength level relied on a field probe monitoring the level adjacent to the EUT, and integrated into a closed-loop control system. This method suffered from large errors caused by scattered fields from the EUT, which even in a good chamber could result in peaks and nulls at various frequencies. These errors can be reduced by using the substitution method to determine the field strength level. The technique is particularly suitable for testing large equipment which gives rise to significant reflections, but it is anyway now the preferred method of field strength measurement for radiated immunity tests and is specified by the CENELEC and IEC standards.

The substitution method involves pre-calibrating the empty chamber by storing, at each frequency, the value of power required to give a certain magnitude of field strength. The EUT is then placed in the chamber and the same power is applied as was used for calibrating the empty chamber, provided that the same field strength is intended for immunity testing. It is usual to calibrate at the standard field strengths of 3V/m and/or 10V/m.

The substitution method of field strength setting relies on the field being adequately constant over a given area in the chamber. The field strength gradient is high near to an antenna but it decreases with increasing distance, and so a large antenna-to-EUT distance is desirable, but as discussed earlier, the limiting factor on distance is usually the power available to drive the antenna for a given field strength. Also, practical chambers do not avoid reflections completely and these will cause standing waves and distortions in the field. At hundreds of MHz, corresponding to wavelengths of one metre or less, the field could vary substantially over small distances.

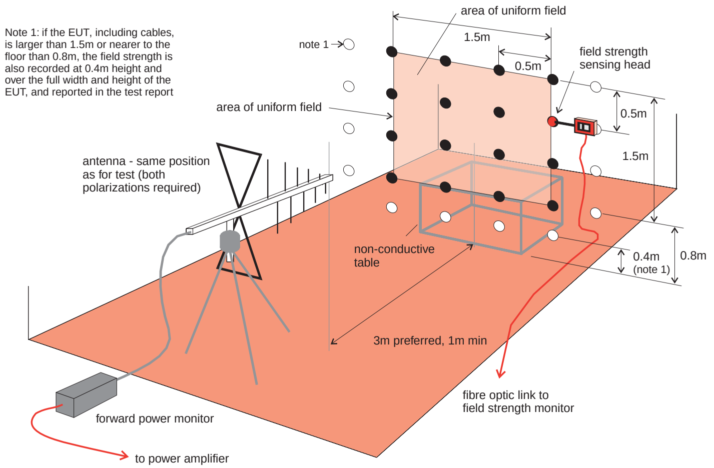


Figure 11 - Field Uniformity definition

As a means of deciding whether a particular chamber is adequate for the requirements of the standard, IEC/EN 61000-4-3 specifies a test of field uniformity to be made at 16 points on a grid as shown above. A smaller uniform area is permissible (minimum 0.5 x 0.5m, i.e. 4 points) provided the EUT and wiring can be fully illuminated within this area.

Measurements are made in the absence of the EUT and the grid corresponds to the position of the front face of the EUT. The field strength at 75% (i.e. 12) of the measurement points must be within the tolerance –0dB/+6dB to be acceptable, though the EN version allows a tolerance of up to +10dB for a maximum of 3% of the test frequencies provided it is stated in the test report.

The tolerance is stated in this asymmetrical way to ensure that at no point over the area does the field drop below the specification value, although at some points and at some frequencies it may over-stress the EUT by up to twice the specification value. This is an unavoidable consequence of the practical difficulty of achieving an adequately uniform field over a large area. It is still better than the older and now unused closed-loop levelling method, which meant that field distortions due to the EUT as well as to room non-uniformity could result in very large field gradients across the dimensions of the EUT.

The control software should be capable of automating the capture and sorting of the field uniformity measurements according to the procedure outlined above. Once a chamber has been calibrated for field uniformity, you should fix all moveable items unrelated to the EUT in position; this is particularly true of the radiating antenna and its cable, any extra absorber that is necessary to meet the uniformity criteria, and any monitoring equipment such as cameras. Alternatively their positions should be marked so that they can be re-established accurately at any time.

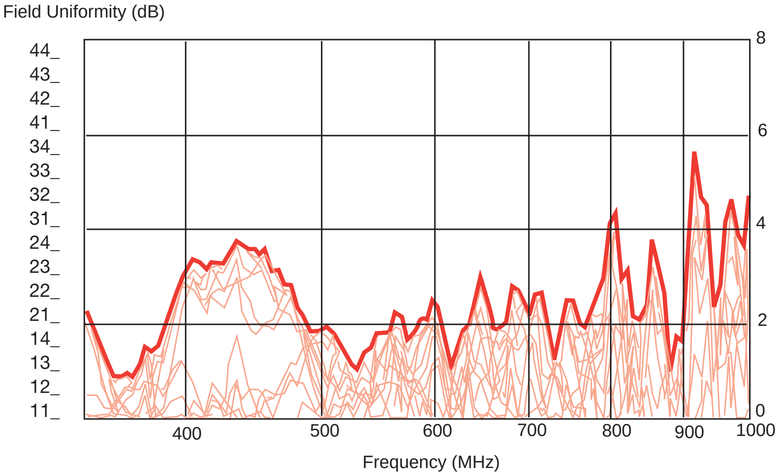


Figure 12 - Field Uniformity plot

The graph shows a typical plot, where each line is the performance at one location. The total envelope after rejecting the worst four points is the room performance. As can be seen, this room meets the requirements. If you want to compare the performance of rooms, you can use either of two comparison criteria:

- If only sufficient points are ignored to just achieve a 6dB curve, the figure of merit is ‘how few points are rejected’
- If exactly 25% of the points are rejected, the figure of merit is “how far below 6dB the curve is”.

Test setup and procedure

The EUT is placed on the usual 0.8m high wooden table (for table top devices) with its front face in the same plane as the uniform field area that was previously calibrated. Both the antenna position and the uniform area are fixed with respect to the chamber. The standard requires at least 1m of connected cable length to be exposed to the field, and recommends the use of ferrite chokes to decouple longer cables. The cable layout cannot be generally specified, but at least some of the length should be in the same plane as one of the polarisations of the antenna.

The EUT is rotated on the table so that each of its four sides, and the top and bottom if it may be used in any orientation, face the antenna in turn, and are coplanar with the uniform area. For each orientation, two sweeps are performed across the frequency range, one in each antenna polarisation. If the frequency is swept from 80 to 1000MHz in 1% steps with the conventional minimum dwell time of 3 seconds per step, each sweep should take about 15 minutes, and the whole test should take over two hours. This though, ignores the need for the software to control the frequency step, including settling and levelling at each new frequency. Depending on the software algorithm, this can increase the time per step (and therefore the total test duration) by 1.5 – 2 times.

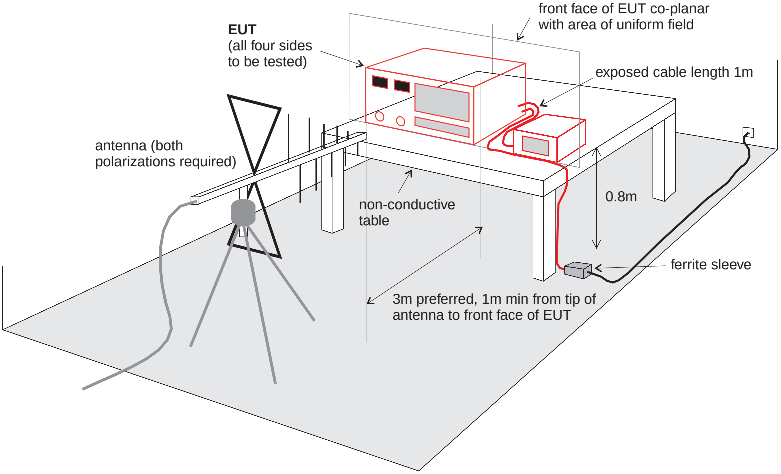


Figure 13 - Radiated Immunity test setup

Field probes

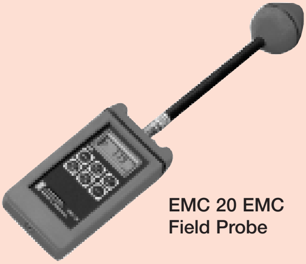
RF field is measured using an isotropic field probe, which reads directly in volts per metre the field present at a given location.

A probe must, obviously, cover the frequency range, including likely future requirements. In addition, it must cover a wide dynamic range. Sophisticated levelling software will use the results of early level step changes to predict the eventual drive level required. The sooner the probe can return valid data, the quicker the software can set the level. During a levelling procedure (especially if the chamber is resonant), the field may rise to several times the target value before the correct level is established. A probe must not be damaged by this high level or lock up due to the over-range.

Resolution is vital and a probe should not reduce this when the range is increased. It should also be linear over as wide a dynamic range as possible. In practice this is a weakness of many probe designs and it is often better to rely on the field probe only at field strengths close to those for which it was calibrated, and use the linearity of the power meter, via the power setting, to determine other levels.

Field Probe

Schaffner field probes can measure RF fields from 1-800V/m. An isotropic sensor measures three orthogonal axes. Fieldstrength data is automatically combined to give a sum of all axes. The sensor is contained in a small volume (approx. 1cm^3) thus reducing the field disturbance, making it ideal for immunity testing.



EMC 20 EMC Field Probe

A field probe is only calibrated for an unmodulated signal. It will not read the correct value if the signal is modulated. Therefore you should always ensure that level setting with a field probe is only carried out with modulation turned off.

An “isotropic” probe will return the same result for a field of a given magnitude regardless of the direction of the field or the orientation of the probe. This is achieved by measuring the field in each of three orthogonal directions and calculating their vector sum. This means that no care has to be taken, when positioning the probe, that it lines up with the polarisation of the antenna and that the probe does not need to be repositioned when the antenna polarisation is changed. Surprisingly, not all supposedly isotropic field probes are in fact fully isotropic. This can be due to the design, if all three of the field measuring elements are not concentric they are measuring the field at different locations. Non-isotropicity can also result from the presence of metal close to the measuring elements.

Monitoring the EUT

In the radiated test, the presence of an operator in the chamber would disturb the field uniformity, as well as exposing the operator to potentially hazardous RF fields. But for every sweep, it is necessary to monitor and record the EUT’s response. So you will have to provide a remote means of monitoring, preferably one that can be linked into the controlling computer so that an automatic record is generated while the sweep is in progress.

If the EUT has a voltage or current output this can be achieved easily via GPIB-connected voltmeters. Electrical status signals can also be monitored easily. In either case it is only necessary to bring the signal out of the test environment through a filtered barrier. It may be helpful to have the EUT running diagnostic software internally which provides a specific status output. For other aspects of the performance it may be necessary to use special support equipment, for example:

- Data generating and validating systems, for digital processing EUTs such as datacomm products;
- Audio signal-to-noise instrumentation, for audio and telephone products;
- Video cameras within the chamber, for EUTs which give visible indications or may show unintended physical movement.

All such equipment must be isolated from the test environment, or must be known to be unaffected by the injected levels of RF.

Testing in TEM cells

As an alternative to chamber testing, transmission line techniques have been used for testing RF immunity since the early days – the open stripline methods of IEC 801-3 and EN 55020 being widespread examples. TEM cells, and in particular the GTEM naturally lend themselves to the continuation of these methods with the extra advantage that no signal is radiated into the near environment. With these methods, the field is developed between two plates of a transmission line and the EUT is placed into this field.

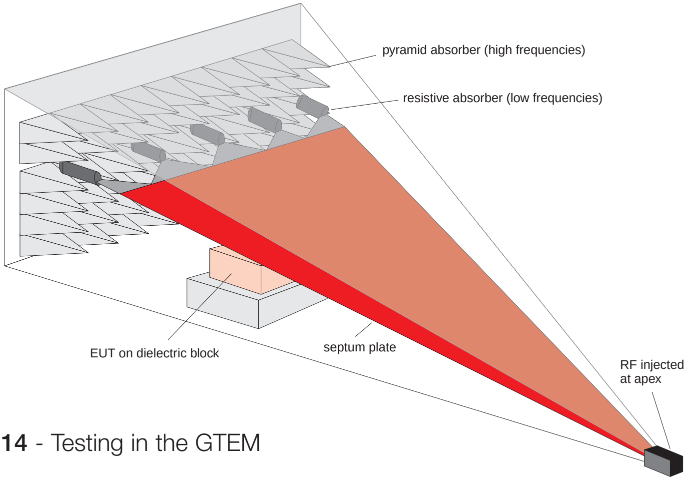


Figure 14 - Testing in the GTEM

GTEM test cell

A full range of eight GTEM cells are available from Schaffner, ranging in size from 250mm for very small EUT up to the very large 2 metre version capable of testing small racks of equipment.

Also available is the GTEM Lite range, which offers a more economical choice for those who need to carry out standard testing without the requirement for testing at the very high frequencies offered by the classic range.

GTEM 'Classic'

GTEM 'Lite'

Two significant advantages of the GTEM are that the upper frequency limit of a TEM cell is extended to over 1GHz, and that its drive power requirement is uniformly lower than that of an antenna at 3m, especially below 80MHz where conventional biconical types become highly inefficient. The drive power for a given field strength is proportional to the square of the height of the septum. Since the septum height flares from one end to the other, small EUTs can be positioned closer to the apex and can consequently be tested to higher field strengths than are available nearer to the terminated end.
The major concern is whether tests done in the GTEM will correlate with tests on the same EUT in an anechoic chamber. Rather less research has been carried out into this correlation than is the case for emissions. However, a draft document has been produced updating the relevant annex of the basic immunity test standard.

The existing annex D of IEC 61000-4-3 allows use of the TEM cell method if the field homogeneity requirements are met, “**and if the EUT and wires can be arranged as required by this section of IEC 1000-4**. Additionally, the arrangement of the EUT and associated wiring cannot exceed one-third of the dimension between the septum and the outer conductor". Of course, this is the most difficult aspect to arrange, for EUTs with external cables, since the cables have to be connected through the wall of the cell, but the whole arrangement must allow for rotation within the cell for testing different polarizations.

An attempt has been made to provide better guidance in the form of a draft amendment to annex D. This adapts the field uniformity requirement of the main standard to allow smaller uniform areas, but requires control of the cross-polar electric field components to better than 6dB below the primary component.
The draft also refers to the EUT and wiring layout, and advises that "wiring is left exposed to the electromagnetic field and is routed above the floor, at either EUT level or along a diagonal, to the exit point in the cell or stripline wall. Routing cable along a conducting wall shall be avoided." Excess cable is bundled within the uniform area.

Reference material

Electromagnetic fields

An electromagnetic wave propagates as a combination of electric and magnetic fields. The ratio of the electric to magnetic field strengths (E/H) is called the wave impedance, and this depends on the nature of the source and the distance d from it. In the far field, $d > \lambda/2\pi$, the wave is known as a plane wave; the field vectors are at right angles to each other and to the direction of propagation, their amplitude decays proportionally to 1/d, and they are in phase. Its impedance is equal to the impedance of free space derived from Maxwell's wave equations, and given by;

$$Z_o = \sqrt{(\mu_o/\varepsilon_o)} = 120\pi = 377\Omega$$

where μ_o is $4\pi \cdot 10^{-7}$ H/m
and ε_o is $8.84 \cdot 10^{-12}$ F/m

In the near field, $d < \lambda/2\pi$, the wave impedance is determined by the characteristics of the source. A low current, high voltage radiator (such as a dipole) will generate mainly an electric field of high impedance, while a high current, low voltage radiator (such as a loop) will generate mainly a magnetic field of low impedance. In general, the E and H fields are not in phase, and they decay at a rate proportional to $1/d^2$ or $1/d^3$.

The region around $\lambda/2\pi$, or approximately one sixth of a wavelength, is the transition region between near and far fields. Figure 15 shows the transition distance as a function of frequency.
Figure 16 shows the wave impedance in the near and far field regions.
In the near field, the possible values of wave impedance are bounded by the maximum and minimum values from a pure electric or magnetic dipole.
In the far field, the wave impedance tends to Z_o.
If the immunity of the EUT is to be properly assessed, then the power in the applied fields should be known. Since the field transducer (above 80MHz) is an electric field antenna, the power is only known if the wave impedance is known. This is another reason why EMC immunity tests should be made in the far field, that is, substantially more than 0.6m (/2) away from the source for a minimum frequency of 80MHz. Tests with the antenna close to the EUT are operating in

a region of unknown field characteristics and therefore do not give a reliable indication of the disturbance immunity.

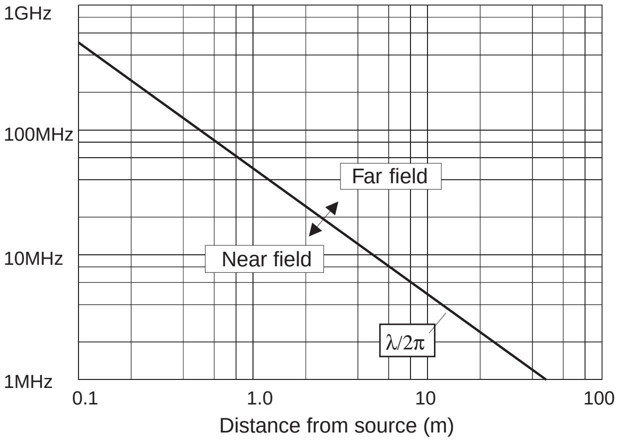


Figure 15 - The transition distance

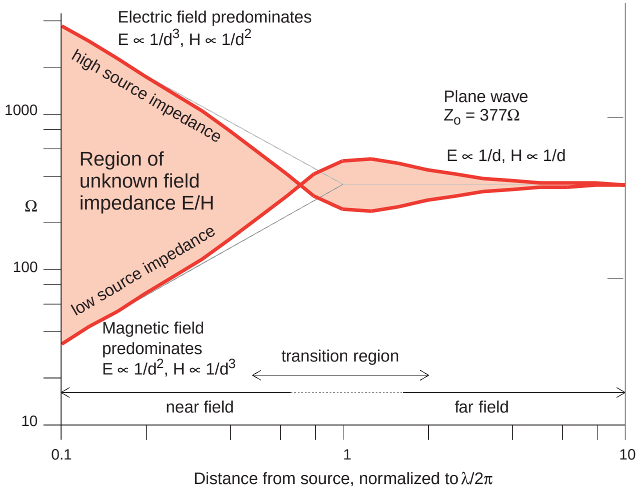


Figure 16 - The wave impedance

There is another definition of the transition between near and far fields, determined by the Rayleigh range. This has to do not with the field structure according to Maxwell's equations, but with the nature of the radiation pattern from any physical antenna (or equipment under test) which is too large to be a point source. For the far field assumption to hold, the phase difference between the field components radiated from the extremities of the antenna must be small and therefore the path differences to these extremities must also be small in comparison to a wavelength. This produces a criterion that relates the wavelength and the maximum dimension of the antenna (or EUT) to the distance from it. Using the Rayleigh criterion, the far field is defined as beyond a distance:

$$d > 2 \cdot D^2/\lambda$$

where D is the maximum dimension of the antenna

Table 1 shows a comparison of the distances for the two criteria for the near field/far field transition for various frequencies and EUT dimensions. For typical EUT dimensions the Rayleigh range determines the far field condition above 100–200MHz.

Frequency	Maximum dimension D (m)	Rayleigh $d = 2D^2/\lambda$ (m)	Maxwell $d = \lambda/2$ (m)
10MHz	2	0.267	4.77
30MHz	2	0.8	1.59
100MHz	0.5	0.167	0.477
	2	2.67	0.477
300MHz	0.5	0.5	0.159
	2	8.0	0.159
1GHz	0.5	1.67	0.0477

Table 1 – Comparison of Rayleigh and Maxwell transition distances

deciBels

In EMC testing, many quantities are referred to in deciBels (dBs). The dB represents a logarithmic ratio (base ten) between two quantities and is unitless.
If the ratio is referred to a specific quantity this is indicated by a suffix, e.g. dBV is referred to 1V, dBm is referred to 1mW.

Originally the dB was conceived as a power ratio, given by:

$$\mathbf{x\ dB} \quad = \quad \mathbf{10 \log (P_1/P_2)}$$

Power is proportional to voltage squared, hence the ratio of voltages or currents across a constant impedance is given by:

$$\mathbf{x\ dB} \quad = \quad \mathbf{20 \log (V_1/V_2) \text{ or } 20 \log (I_1/I_2)}$$

Conversion between voltage in dBV and power in dBm for a given impedance Z ohms is:

$$\mathbf{V(dB\mu V)} \quad = \quad \mathbf{90 + 10 \log (Z) + P(dBm)}$$

Actual voltage, current or power can be derived from the antilog of the dB value:

$$\mathbf{V \quad = \quad \log^{-1} (dBV/20) \text{ volts}}$$
$$\mathbf{I \quad = \quad \log^{-1} (dBA/20) \text{ amps}}$$
$$\mathbf{P \quad = \quad \log^{-1} (dBW/10) \text{ watts}}$$

Expressing values in dB means that multiplicative operations (such as attenuation and gain) are transformed into simple additions. For example, a signal of 42µV (32.5dBµV) fed via a transducer with conversion factor 0.67 (-3.5dB) and a cable with attenuation loss 0.75 (-2.5dB) into an amplifier of gain 200 (46dB) will result in an output of:

$$\mathbf{V_{out} \quad = \quad 32.5 - 3.5 - 2.5 + 46.0 = 72.5dB\mu V = 12.5dBmV = 4.2mV}$$

A simple rule of thumb:
When working with power, 3dB is twice, 10dB is ten times;
When working with voltage or current, 6dB is twice, 20dB is ten times.

The following tables allow you to look up a dB value for a given ratio, and also to convert from dBµV (voltage) to dBm (power) in a 50 ohms impedance.

Table 2 - **dB ratios**

dB	**Voltage or current ratio**	**Power ratio**	**dBm** (50Ω, column 1 in dBµV)
-20	0.1	0.01	-127
-10	0.3162	0.1	-117
-6	0.501	0.251	-113
-3	0.708	0.501	-110
0	1.000	1.000	-107
0.5	1.059	1.122	-106.5
1	1.122	1.259	-106
2	1.259	1.585	-105
3	1.413	1.995	-104
4	1.585	2.512	-103
5	1.778	3.162	-102
6	1.995	3.981	-101
7	2.239	5.012	-100
8	2.512	6.310	-99
9	2.818	7.943	-98
10	3.162	10.000	-97
12	3.981	15.849	-95
14	5.012	25.120	-93
16	6.310	39.811	-91
18	7.943	63.096	-89
20	10.000	100.00	-87
25	17.783	316.2	-82
30	31.62	1000	-77
35	56.23	3162	-72
40	100	10,000	-67
45	177.8	31,623	-62
50	316.2	10^5	-57
55	562.3	$3.162 . 10^5$	-52
60	1000	10^6	-47
65	1778	$3.162 . 10^6$	-42
70	3162	10^7	-37
75	5623	$3.162 . 10^7$	-32
80	10,000	10^8	-27
85	17,783	$3.162 . 10^8$	-22
90	31,623	10^9	-17
95	56,234	$3.162 . 10^9$	-12
100	10^5	10^{10}	-7
110	$3.162 . 10^5$	10^{11}	3
120	10^6	10^{12}	13

VSWR, VRC and return loss

These three terms describe the match presented by a source or load; they all refer to the same phenomenon but in different ways.

VSWR (Voltage Standing Wave Ratio) is the ratio of maximum to minimum voltage along a transmission line. A high VSWR implies a poor match. VSWR is always ≥1. A short circuit or open circuit load produces an infinite VSWR.

VRC (Voltage Reflection Coefficient) Γ is the inverse ratio of the sum and difference of the characteristic impedance of the transmission line (Z_0) and the load impedance (Z_L). A high VRC implies a poor match. VRC is always ≤1. A short circuit or open circuit load produces a VRC of -1 or 1 respectively.

Return loss R is simply the Voltage Reflection Coefficient expressed in dB. A low value of return loss implies a poor match.

The three parameters are related by:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad |\Gamma| = \frac{VSWR - 1}{VSWR + 1} \qquad VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad R = -20\log(|\Gamma|)$$

Return Loss R dB	**VSWR**	**VRC Γ**
1	17.391	0.891
2	8.724	0.794
3	5.848	0.708
4	4.419	0.631
5	3.570	0.562
6	3.010	0.501
10	1.925	0.316
15	1.432	0.177
20	1.222	0.100
25	1.119	0.056
30	1.065	0.032
35	1.036	0.018
40	1.020	0.010
50	1.006	0.003

Table 3 - **VSWR and VRC versus return loss**

Mismatch error

No device presents a perfect 50 ohm match to its connected cable.
All equipment presents a mismatch at its terminals (poor VSWR) which varies with frequency. This creates an additional uncertainty in the power measured at the far end of the cable, according to Figure 17.

Impedance mismatch can be improved by fitting an attenuator between the equipment exhibiting a poor VSWR and the point at which a good match is desired. The effect of the attenuator is to reduce the reflected signal, but at the expense of an overall loss of signal. The improvement, in terms of matched VSWR versus original VSWR for typical attenuator values, is given in Figure 18.

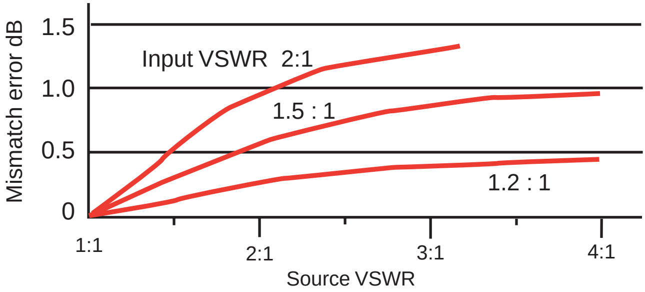


Figure 17 - Mismatch error

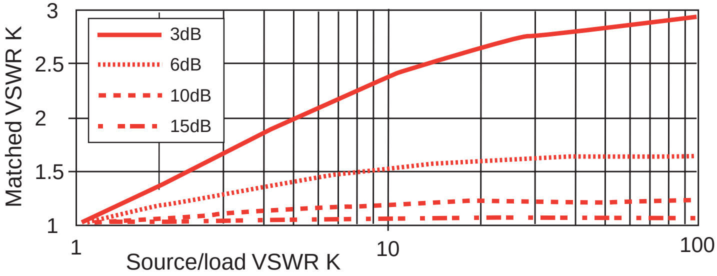


Figure 18 - Improvement of matching with an attenuator

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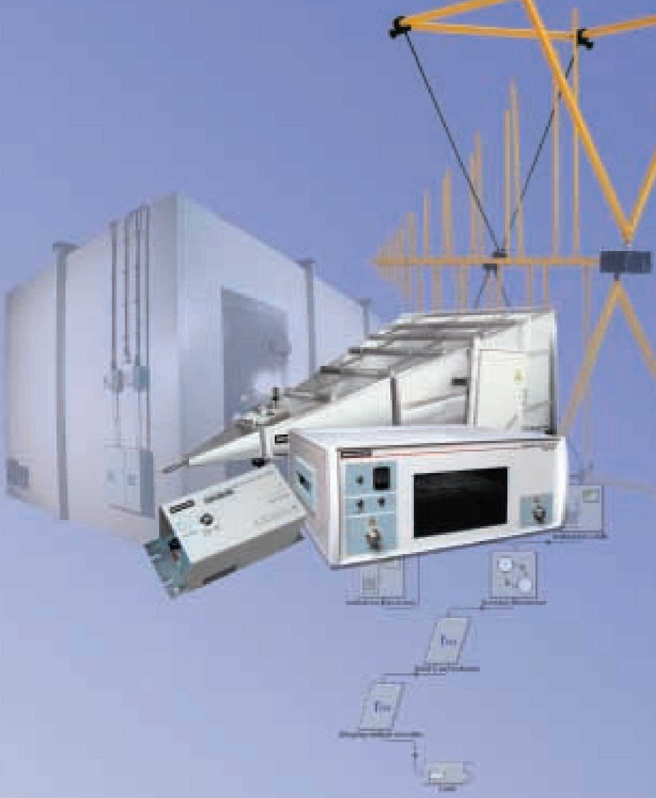

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