Uncertainties of immunity measurements

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DTI-NMSPU project R2.2b1

Main report

This document is the final report of Project R2.2b1 of the National Measurement System Policy Unit's programme for electrical measurement. The central aim of this programme is to provide a minimum national measurement infrastructure for electrical and related quantities in support of trade, quality assurance in industry, innovation and a range of important social activities. The aim of the project was to review and investigate the uncertainties associated with the test methods for conducted and radiated immunity to radio frequency interference.

The project partners were Schaffner EMC Systems Ltd and Elmac Services. Schaffner are a leading manufacturer of EMC test equipment and operate a UKAS accredited calibration laboratory. They are represented on international standards committees concerned with EMC measurements. Elmac Services operate as a consultancy on all aspects of EMC, including test, measurement and design. Their principal is an EMC technical assessor for UKAS and SWEDAC.

The project team and their responsibilities were as follows:

- The project was managed by Ray Hughes of Schaffner EMC Systems.
- The work programme and report were written and reviewed by Tim Williams of Elmac Services, and Stan Baker and Alex Piper of Schaffner EMC Systems.
- The bulk of the experimental work was carried out by Dave Feasey of Schaffner EMC Systems.

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Main report

Table of contents

(The executive summary and best practice guide is distributed separately)

1 Introduction

1.1 Background

EMC describes the compatibility of an electrical or electronic apparatus with its electromagnetic environment and by extension with other apparatus within that environment. Such other apparatus can include portable or fixed radio transmitters which generate a high level electromagnetic field in their neighbourhood. Examples include cellular mobile phones or other personal communications equipment, broadcast transmitters and RF-generating industrial equipment. Electronic equipment must be sufficiently immune from these fields to be able to operate as expected within this environment.

This requirement is now mandatory for all products placed on the market or taken into service under the provisions of the European EMC Directive 89/336/EEC. That Directive allows products which meet the provisions of harmonised standards to enjoy a presumption of conformity with its essential requirements. There are several such standards harmonised for various electromagnetic phenomena; they all apply specific tests, which in the case of immunity require that the product is observed for continued correct operation while the appropriate electromagnetic stress is applied.

Successfully passing these tests is now a requirement for placing a product on the European market. But in addition, some products may have safety-critical aspects in that their continued correct operation is essential to the safety of a system or machine. Thus immunity from electromagnetic stresses is of particular importance to these products and the correct testing of this immunity assumes a significance greater than merely meeting market access requirements.

For testing immunity from RF stress, methods described in two complementary international standards and their European equivalents are used:

- IEC 61000-4-6, for conducted disturbance induced by radiated fields, from 150kHz to 80MHz (and possibly up to 230MHz);
- IEC 61000-4-3, for radiated fields from 80MHz to 1GHz (and potentially higher).

Despite their status as international standards, these methods are known to suffer from considerable uncertainties, partly because of variations in the applied stress and partly because of the unpredictable ways in which the equipment under test (EUT) reacts to this stress. These uncertainties lead manufacturers of electronic equipment to over-engineer their products in order to ensure a test pass, with consequent cost penalties.

The high capital investment needed to perform proper standard tests in-house puts this option out of reach of many SMEs, forcing them to rely on external test laboratories for compliance testing. While this situation cannot be improved in the short term, better control of the uncertainties offered by these laboratories would give such manufacturers more confidence in the integrity of the test and the likelihood of a successful outcome, with attendant reduction in their development costs.

1.2 Critical technical issues

Radio frequency immunity testing of an electronic product requires the application of a stress field or voltage at a constant known level across a wide frequency range. The product under test is not specifically designed to have this stress applied to it and therefore the coupling methods chosen must be applicable to any type of construction. When the RF stress is applied it creates internal signals which potentially combine with the desired operating signals to cause various types of malfunction.

Because of the variation in dominance of different coupling routes, the test standards have evolved two complementary methods:

- via the connected cables, from 150kHz to 80MHz and occasionally above;
- via radiated field, from 80MHz to 1000MHz and occasionally above.

1.2.1 Uncertainty sources

The disturbance mechanism includes several sources of uncertainty which fall into two main categories – those associated with the actual stress applied and those dependent on the design of the EUT and its ancillary equipment.

- The voltage or current induced at the relevant port for cable testing depends on the choice of transducer, as the standard allows for three different types. In situations where any one of these three types may be chosen for testing it is apparent that the failure stress level can depend on this choice and the associated variability should be accounted for in the uncertainties. Since all three types are permitted it would be difficult to argue that one gave more ‘precise’ results than another.
- Once the transducer has been selected for a conducted immunity test, the applied stress is determined by the impedances of the coupling source, the cable and the EUT and AE (for the clamp methods). These in turn are affected not only by the design of each but also by the physical layout of the test set-up.
- For radiated immunity measurements the most important source of uncertainty may be the anechoic chamber in which the test is performed. If using different chambers gives different results due to the wide range of available chambers and the rather imprecise field uniformity requirement (dictated by the difficulties associated with attempting to generate uniform fields) this variability should be included in the uncertainty budget and would need to be linked to a ‘Quality’ factor for the chamber. (A very large, well lined chamber may have total field non-uniformities of less than 6dB at nearly all frequencies and, as such, would have a high Quality factor.)
- The voltage or current induced in the EUT structure by radiated testing depends on the relative geometry of the field and structure, and their impedances. Again, these are affected by the EUT design and the layout of the test set-up.
- Once internal disturbing signals are generated within the EUT by either mechanism, their interaction with the circuit operation may take any of several forms. A large class of these interactions are non-linear, and therefore the relationship between induced disturbance – which itself is subject to uncertainty – and EUT response is affected by this non-linearity.

The project described here applies a review and investigation programme to each of these issues.

1.2.2 Investigation of uncertainties

The uncertainty mechanisms that have been investigated are:

1.2.2.1 Conducted coupling uncertainties

- Variation due to different transducers, theoretical and practical; involving an analysis of the relevant differences, with a practical validation of this analysis using a standardised load and a selection of actual transducers;
- Variation due to layout, theoretical and practical; involving an analysis of the effects of cable length and physical separation from the ground plane, with a practical validation of this analysis using an example EUT and a selection of actual transducers;

1.2.2.2 Radiated coupling uncertainties:

- Variation due to chamber performance and level setting with respect to field uniformity, with an analysis of field uniformity data from a total of 44 different test chambers;
- Variation due to layout and field geometry, theoretical and practical; involving an analysis of field coupling to simple geometrical structures representing the EUT, with a practical illustration using an example EUT;

1.2.2.3 Effects of EUT non-linearities

- quantifying the effects of induced RF voltage on a range of typical analogue and digital circuits in order to identify the degree to which non-linearities modulate the uncertainties in applied disturbance voltage.

1.3 Areas not covered by this study

UKAS LAB34 [43] presents a number of factors that may contribute to the uncertainty of these tests, particularly with respect to the performance of the generating and calibrating equipment. These include the calibration uncertainty of the field measuring probe or the RF voltmeter; the margin inherent in the level setting acceptance window; drift in the forward power measurement; mismatch between the amplifier and conducted transducers; and contributions to the field level from amplifier harmonics. Since these contributions are well established and understood we have not investigated them for this report.

A further question that has not been addressed is how the measurement uncertainty value that finally results, is to be applied to the test method. Should the applied field strength be adjusted (upwards) to reflect the calculated uncertainty, or not? This question affects the confidence level pertaining to the final result. It is addressed in LAB34, and some of our investigations (particularly with respect to the issue of under-testing discussed in sections 3.4 and 3.5) are relevant to it, but because of the limitations of the assigned project we have not considered it here.

In the conducted immunity standard para 7.3, a procedure is given for clamp injection when the common mode impedance requirements cannot be met, which limits the injected current using a monitor probe. We have not considered this method in any detail.

1.4 Recommendations for further research

The scope of the project have limited the work that could be done, but it has become clear that some areas would benefit from further investigation. These are discussed here.

The procedure of IEC 61000-4-6 para 7.3 mentioned above has the potential to introduce substantial extra sources of uncertainty. These should be investigated fully.

The work described here has taken only one type of EUT as its model. While the model was chosen to represent a large class of EUT types, generalisation of the results to many other types (larger or smaller) would be dangerous without further work to ensure that the model is valid. This would investigate particularly the effects of size and shape, properties of the shielding enclosure, impedance variations at the cable ports, and field distribution within the enclosure. These issues should be looked at for both radiated and conducted test regimes.

For radiated immunity, the results suggest that considerable extra work on coupling to cables, both modelled and practical, would be justified. This should concentrate on finding practical ways to specify cable length, layout and termination that could be implemented by laboratories on many types of EUT, and given these constraints, quantifying again the uncertainties to be expected.

Further work on refining the NSD parameter to describe chamber performance would also be worthwhile. It may be possible and helpful to integrate its use into the standard itself.

2 Conducted immunity: IEC 61000-4-6

2.1 A description of the standard

The conducted RF immunity test is defined in IEC 61000-4-6: 1996. This was published also in Europe as EN 61000-4-6 without modification. A second edition is in draft form in IEC SC77B as document no 77B/345/CDV. The intended timescale for publication of the second edition is 2006.

Clause 6 of the standard defines the test equipment and clause 7 defines the test set-up. These two clauses form the bulk of the standard and they are the most relevant to this report.

2.1.1 Test equipment: Clause 6

The test equipment includes the test generator and the coupling and decoupling devices (transducers). The latter are considered in more detail in section 2.2 below. The principal components of the test generator are an RF signal generator covering the required frequency range, a broadband power amplifier, and a power attenuator of at least 6dB between the output of the amplifier and the coupling transducer. The output rating of the power amplifier must be sufficient to deliver the required stress level via the chosen transducer, allowing for excess power required by modulation and the loss in the 6dB attenuator. The attenuator is needed because the impedance of the test generator defines the source impedance seen by the tested line and is crucial in achieving a defined stress level. By itself, the power amplifier is not likely to have a sufficiently well defined output impedance. The attenuator reduces the mismatch and brings the source impedance into an acceptable range.

It is noteworthy that while the original standard specifies (in Table 2) a VSWR of less than or equal to 1.2:1 for the source impedance, a note in the standard says that the attenuator can be omitted if the output impedance of the power amplifier remains within specification under any load condition. Few laboratories are able to verify this requirement and so the attenuator is used as a matter of course. This note is retained in the latest draft of the second edition (77B/345/CDV) but the specification of 1.2:1 has been deleted from Table 2. This is clearly a regression since it is now impossible to ascertain what “remaining within specification” means.

2.1.2 Setting the test level

The required stress level is set using a substitution method. That is, the power required to achieve a given stress through the transducer into a calibration fixture across the frequency range is recorded; the same power is then re-played with the transducer connected to the equipment under test (EUT) cable. The stress level is therefore defined as a voltage into a fixed resistive impedance, which in general will not be the same as the actual voltage delivered to the EUT.

Although all transducers of a given type should have similar losses, each individual transducer will have its own transfer characteristic and therefore each should carry an individual calibration file.

The standard implicitly allows the output level to be set either at the signal generator output or at the power amplifier output. An explicit note has been added to the draft second edition confirming that this is acceptable provided that “it can be guaranteed that the test equipment including the signal generator and power amplifier works always in the same condition, e.g. drift of the power amplifier gain which insures constant harmonic distortion”.

2.1.3 The test set-up: Clause 7

The principle of the test is to excite disturbance fields within the EUT by applying the stress to certain selected cables entering the EUT (Figure 1). The stress is applied through a defined non-zero source impedance. This implies that the common mode impedance of the EUT and of its connected cables must be carefully controlled, so that the applied voltage remains predictable. The common mode impedance is defined as 150 ohms both for the source impedance and for the impedance of other cables connected to the EUT. Therefore it is necessary to use networks to stabilise this impedance or to decouple it, so as to ensure that unwanted variations have little effect on the test, and to make sure that the layout of the test is controlled so that variations due to stray coupling are minimised. Clause 7 of the standard covers these issues.

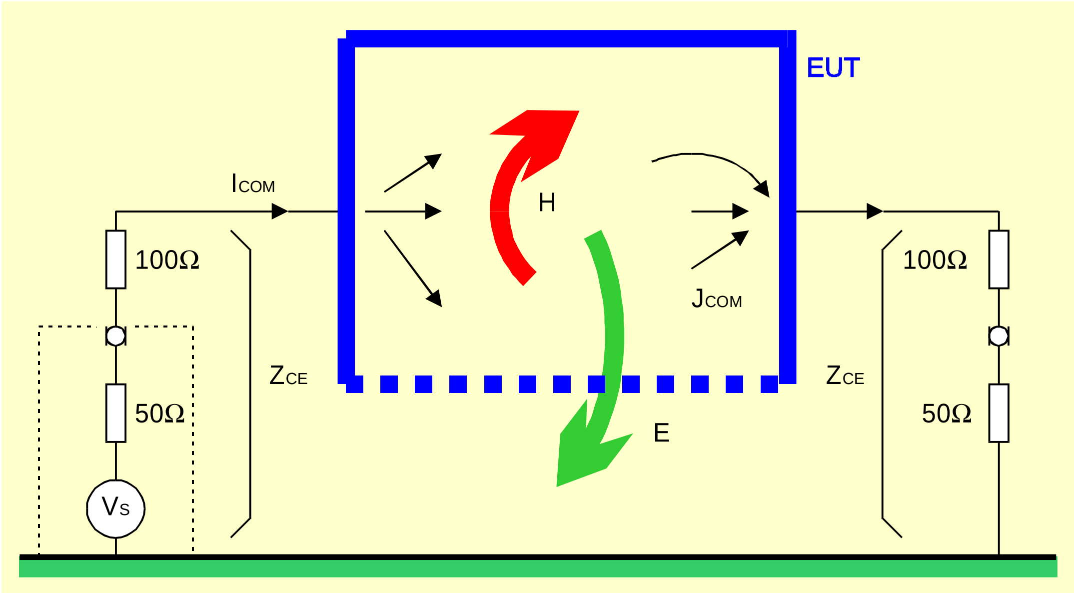

Figure 1: principle of applied stress (after IEC 61000-4-6 Fig 2a)

Clause 7 gives:

- rules for selecting the injection method and the test point(s);
- the extra procedure to be followed for clamp injection;
- the layout of the EUT.

The draft second edition expands and modifies these instructions and also adds instructions for CDN and direct injection methods.

2.2 The three transducers

The standard provides for three generic types of transducer. These are:

- Coupling/decoupling networks (CDN), which may also include direct injection onto a screened cable
- the EM-clamp
- the current injection probe

2.2.1 CDN and direct injection

The CDN method is invasive onto the cable, that is, a direct connection is made to all conductors in an unscreened cable or to the screen in a screened cable. The stress voltage is applied from the test generator through a series resistance onto this connection. On the side of the connection away from the EUT, the common mode impedance is increased by applying a common mode choke. Thus the source impedance is determined almost entirely by the resistor value, in series with the output impedance of the generator. Figure 2 shows the basic principle of this coupling method.

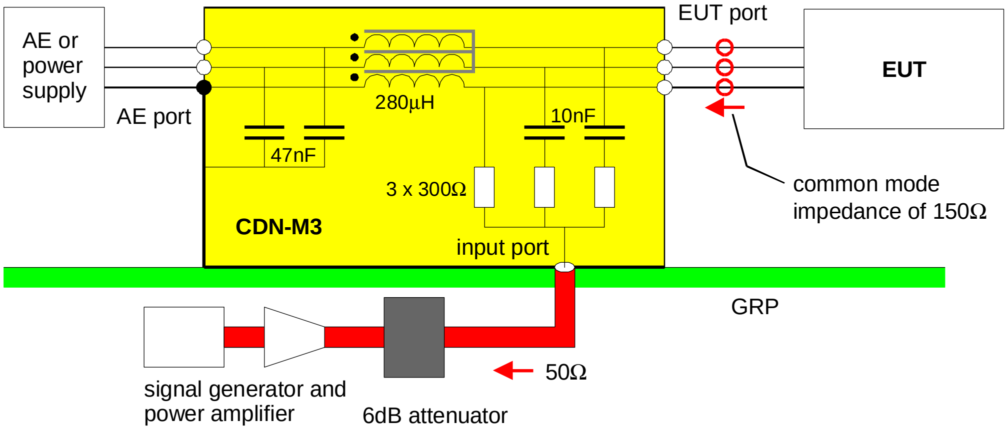

Figure 2 Coupling via CDN or direct injection (example for 3 line mains cable)

The standard requires the magnitude of the impedance measured at a grounded vertical plane 30mm from the EUT port terminals to be as follows:

Table 1 CDN impedance specification

0.15 – 26MHz	26 – 80MHz
150Ω ± 20Ω	150Ω +60/-45Ω

This specification must be met with the AE terminals both short-circuited and open-circuited, thus ensuring good decoupling. The frequency range of application may be extended in some cases up to 230MHz. In this case Annex B of the standard requires that the impedance specification in the second column above is extended up to 230MHz.

The advantages of the CDN/direct injection method are that the loss through the transducer is low, so the least power is needed to reach the desired stress level, and the AE side of the transducer is well decoupled from the EUT side. Variations in layout or connection at the AE side have no significant effect on the test.

The disadvantage is that because the coupling is invasive, there are only certain classes of cable for which the method is suitable – for instance mains or DC power, or low-impedance unbalanced audio. A general test laboratory will have to keep a selection of CDN units for all the likely cable types expected, but this will never cover all possible types. On the other hand, a manufacturer may be prepared to hold CDNs for all the cable types used on his products. Even so, devising a CDN for wideband unscreened multi-way cables is not trivial and it is very easy for the device to degrade the wanted signals carried in the cable, which would make it unacceptable for the test.

For this reason, a universal test method also needs a non-invasive way of coupling the stress to “difficult” cable types. IEC 61000-4-6 provides two alternatives for this purpose.

2.2.2 The EM-clamp

The EM-clamp is a transducer which can be clamped over the cable to be tested and which is constructed to provide both electric (capacitive) and magnetic (inductive) coupling, hence the designation “EM”. The coupling modes are so arranged that there is a degree of directivity between the EUT side and the AE side of the clamp, at least above 10MHz. As we shall see later, this is a significant point. The two modes of coupling are illustrated in Figure 3, and a graph of typical coupling factors is shown in Figure 4.

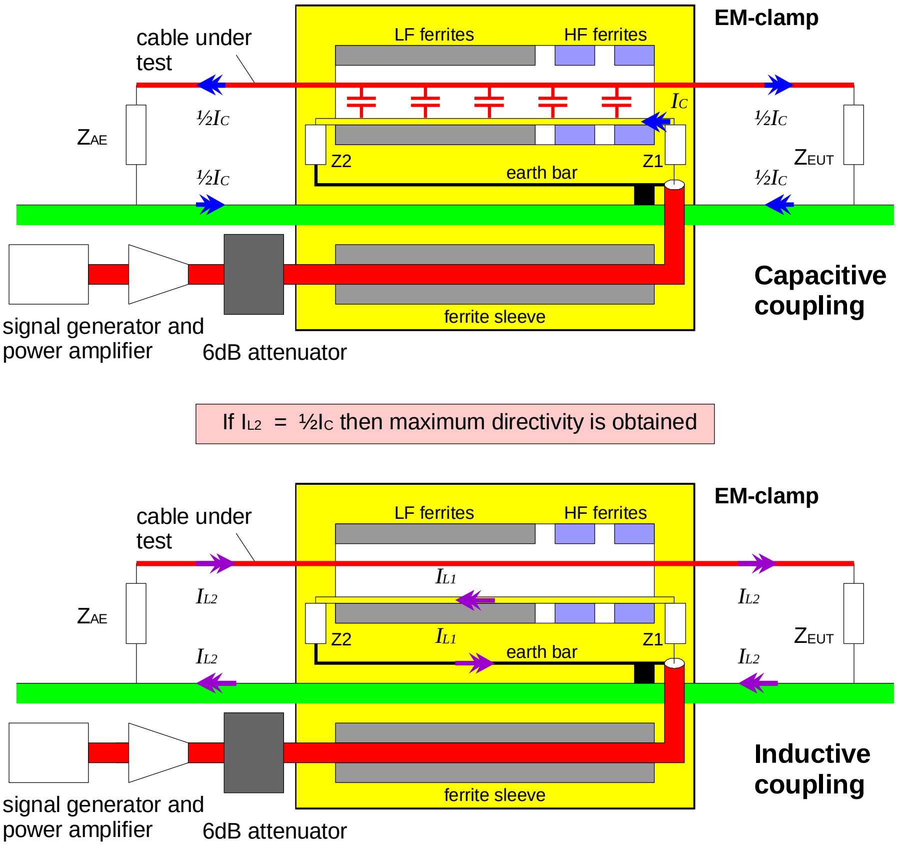

Figure 3 Coupling modes of the EM-clamp

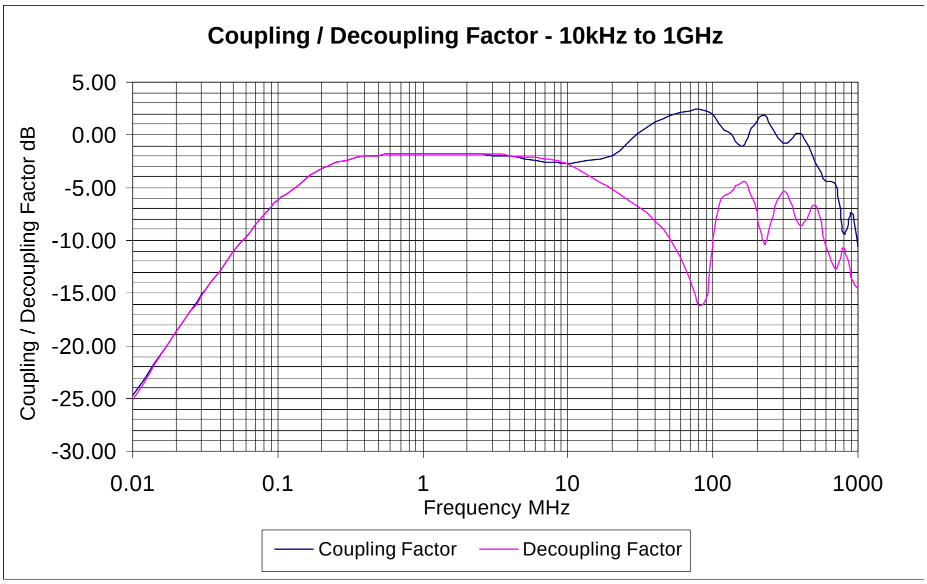

Figure 4 Typical EM-clamp coupling factor (directivity is ratio of coupling to decoupling)

The advantage of the EM-clamp, apart from its non-invasive nature, is that it has a reasonably good coupling factor (although not as good as the CDN) and therefore still needs relatively low power for a given stress level. Its directivity attenuates high-frequency effects of the cable layout on the AE side.

Because it uses a series of ferrite sleeves to provide the inductive coupling, it is quite long with a relatively narrow inside diameter. This makes it bulky to use and restricts its application for short or large-diameter cables. Below 10MHz its directivity is negligible and therefore the AE low frequency common mode impedance is not decoupled. It does not provide an accurate source impedance of 150Ω across the frequency range.

It is possible to add a second ferrite decoupling clamp at the AE end of the EM-clamp, and this practice has been discussed by the originator of the method [13]. If this is used, the independence of the result from the impedance at the AE is improved below 10MHz. Above 10MHz the additional clamp has no influence. The advantage of this improved independence is balanced by the disadvantage of a much higher impedance seen by the EUT (again the effect is below 10MHz, most pronounced around 1MHz), which has to be compensated by a higher input into the clamp. The cores of the second clamp must be selected to give a compromise between better isolation from impedance variations and the need to provide a higher power input at certain frequencies. The European pre-standard ENV 50141 shows this method in practice, but the approach was deleted from IEC 61000-4-6 and as a consequence few if any laboratories use it.

2.2.3 Current injection probe

The standard also provides for the use of a current clamp or bulk current injection (BCI) probe. This device, like the EM-clamp, is non invasive and applies the stress via inductive coupling only. The probe forms a transformer with a toroidal core; the primary is a number of turns wound around the toroid, and the secondary is the cable under test, which is effectively a single turn through the toroid (Figure 5). The assembly is shielded to prevent capacitive coupling to the cable. Neither decoupling nor impedance stabilisation is provided by this device.

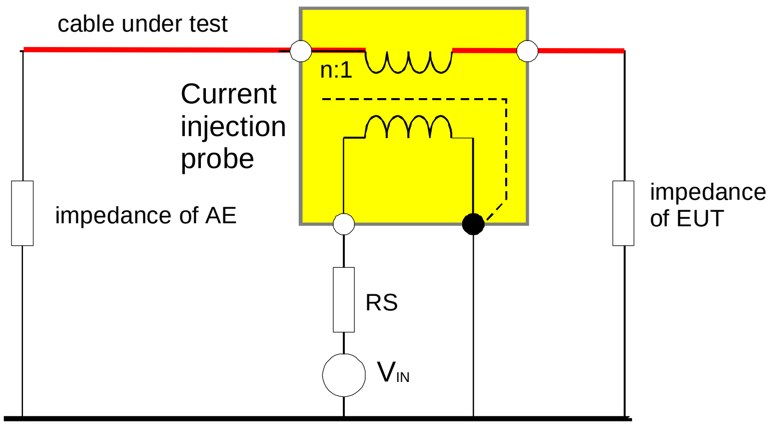

Figure 5 The current injection probe

The coupling factor for this probe depends on the turns ratio. The higher the ratio, the less signal is induced in the cable and the greater the power that must be applied for a given stress level. The standard refers to a 5:1 turns ratio which has a minimum theoretical loss of 14dB, and greater than this in practice. However, many laboratories which have been using this test method for military or automotive applications already have probes of lower turns ratio (typically 1:1) and naturally expect to be able to apply them for IEC 61000-4-6. In fact, probes with turns ratios of 5:1 do not appear to be commercially available.

The standard does not explicitly mandate a turns ratio of 5:1. Instead, Annex A requires that “the transmission loss of the test jig shall not exceed 1dB when tested in a 50Ω system with a current clamp installed and terminated at its input port by a 50Ω load”. It can be shown [16] that the minimum turns ratio that will achieve this specification is 2:1. The implications for the applied stress of this specification are explored further in section 2.11.

The practical advantage of the current probe is that it is smaller than the EM-clamp and normally has a larger internal diameter, thus allowing its use on a much wider range of cable types.

2.3 Literature review

Available literature on the conducted immunity test, starting with the standard itself, is referenced in section 5.1. There is a fairly considerable body of literature regarding the test method using the bulk current injection (BCI) probe since this has historically been used for automotive and military testing for many years. Most of this literature does not treat the special issues arising from its use in the IEC 61000-4-6 test. Published material regarding the CDN and EM-clamp methods is harder to find. This may be because the CDN method, in particular, is not controversial. However there are two sources which have direct relevance to the work of this project, which compare the BCI current probe and EM-clamp methods of injection in some detail. These are the papers presented to the standards working groups in 1991 and 1992 by R Bersier and colleagues of the Swiss PTT, the inventor of the EM-clamp [10]-[15], and a more recent M.Sc. thesis by N Monteyne at the University of York, considering these two methods in the context of the agricultural machinery EMC test standard ISO 14982 [8],[9]. Data from these two sources is referenced in this project in section 2.11.

2.4 A circuit model of the test

A full description of the circuit model is given in Annex A.

2.4.1 The total equivalent circuit

The conducted immunity test can be expressed in purely circuit terms quite successfully. As the frequency increases so radiation effects become significant, but up to the typical upper limit of 80MHz it appears that a circuit model can easily represent the principal factors at work. The model must take into account:

- the common-mode impedance of the whole EUT
- the input impedance of the EUT cable port being tested
- the transmission line characteristics of the cable being tested
- the coupling characteristics of the transducer
- the common mode impedance of the AE at the other end of the cable being tested

Regarding the transducers for the moment as "black boxes", the test circuit model used in this report is as shown in Figure 6.

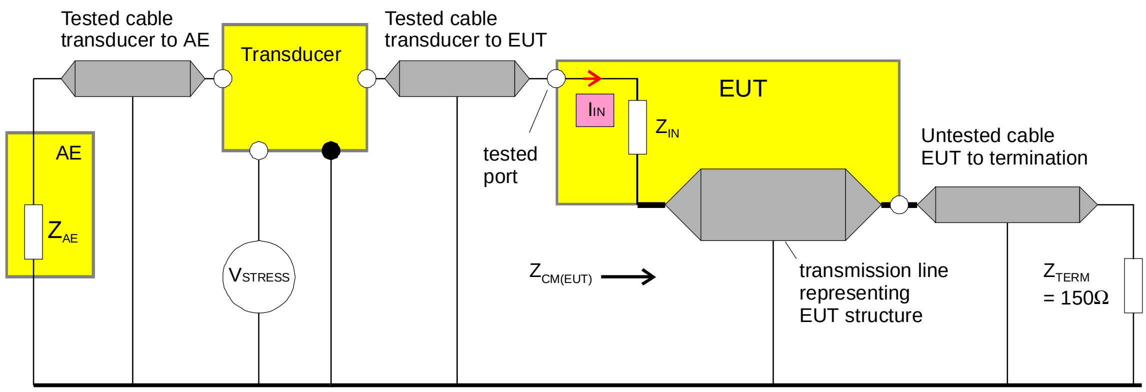

Figure 6 Circuit model of the conducted immunity test

The EUT is mounted a fixed distance from the ground plane (10cm) and a typical EUT is likely to include a large metal structure, either a screening enclosure or if this is absent, a PCB ground plane. The EUT common mode impedance $Z_{CM(EUT)}$ can then be represented as a parallel plate transmission line whose parameters are defined by the length, width and height above the ground plane of this structure. The standard requires untested cables to be terminated in a 150Ω common mode impedance, typically provided by feeding them through CDNs with terminated input ports. Both the untested cables and the cable under test can be represented also by transmission lines connected to the EUT chassis, their length corresponding to the cable length and their characteristic impedance determined from their diameter and height above the ground plane.

The input impedance Z_{IN} of the EUT port being tested depends entirely on the detailed design of the EUT. This is the common mode impedance between the port connector pins and the ground reference of the EUT – not the ground plane of the test setup. Different designs will have different characteristics: for instance a screened cable termination to the EUT case will have a very low impedance, while an unscreened cable filtered by a series choke will have a high impedance. Filtering by parallel capacitors will give a low impedance, and unfiltered, unscreened connections (if they still exist!) will have impedances determined by the circuit operation.

Finally, it can be seen that the impedance presented by the AE (associated, or auxiliary, equipment), transformed by the length of cable acting as a transmission line between the transducer and the AE, will affect the circuit if it is not decoupled by the transducer. This is the case for both the current injection probe and EM-clamp, but not for the CDN.

To compare the effects of the various factors it is possible to consider the stress in terms of the disturbance current I_{IN} flowing at the input port of the EUT. For a given impedance at this point, variations in the external parameters should be expected to give minimum variations in this current. Naturally the actual effect of the stress on the EUT – changes in the monitored performance – is unknowable from this simplified circuit and is in any case entirely EUT-dependent. Also, the frequency dependence of this current is not necessarily flat, because of variations in Z_{IN}, $Z_{CM(EUT)}$ and Z_{AE} even if the applied stress into the calibration jig is constant with frequency, as it should be.

The parameter which is used for all comparisons in this report is the ratio of I_{IN} as measured or predicted, and the applied stress level as set in the calibration jig according to the standard.

2.4.2 Models of the transducers

Each transducer can also be modelled in circuit form, taking the circuit components from the known design of the transducer and estimating stray reactances in the first instance. The final circuit values are then adjusted until the behaviour of the “virtual” transducer (its coupling factors and EUT-port impedance curve) closely represents that found in calibration of the real device.

2.4.2.1 CDN

This model should represent all generic CDNs. Its values were adjusted to match the calibration characteristic of the M1 CDN used for the practical work. The circuit closely follows that given in the standard with the addition of expected stray components.

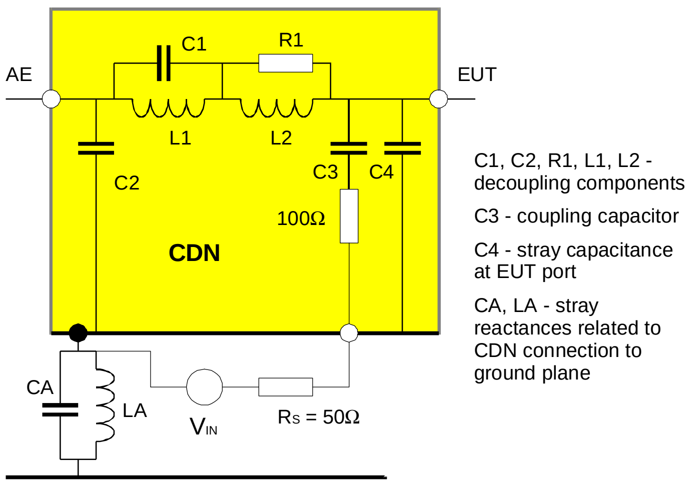

Figure 7 Circuit model of the CDN

2.4.2.2 Current injection probe

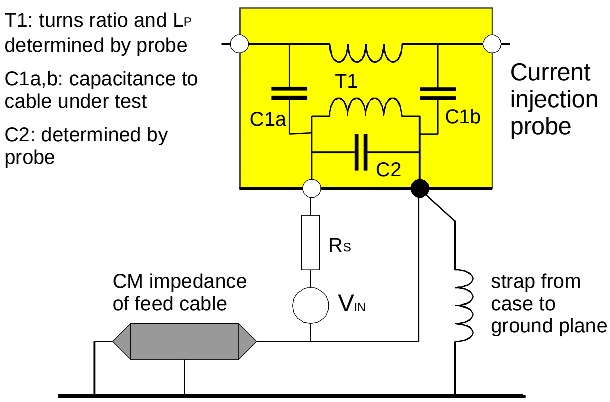

Figure 8 Circuit model of the current injection probe

This model represents generic injection probes. The turns ratio and primary inductance L_P were chosen to match the known specification of the probe used for the practical work, with stray components deduced from network analyser measurements of the probe.

2.4.2.3 EM-clamp

This model represents the Lüthi EM-101 clamp. This is the most widely used clamp in typical test laboratories and is the one used for practical work in this project. It is based upon the design published in the standard but differs from it slightly in that the impedance Z1 shown in the standard is not implemented. The model is unable to take into account the frequency-dependent properties of the ferrite cores, but this does not seem to seriously affect its ability to mimic the actual performance of the clamp in use.

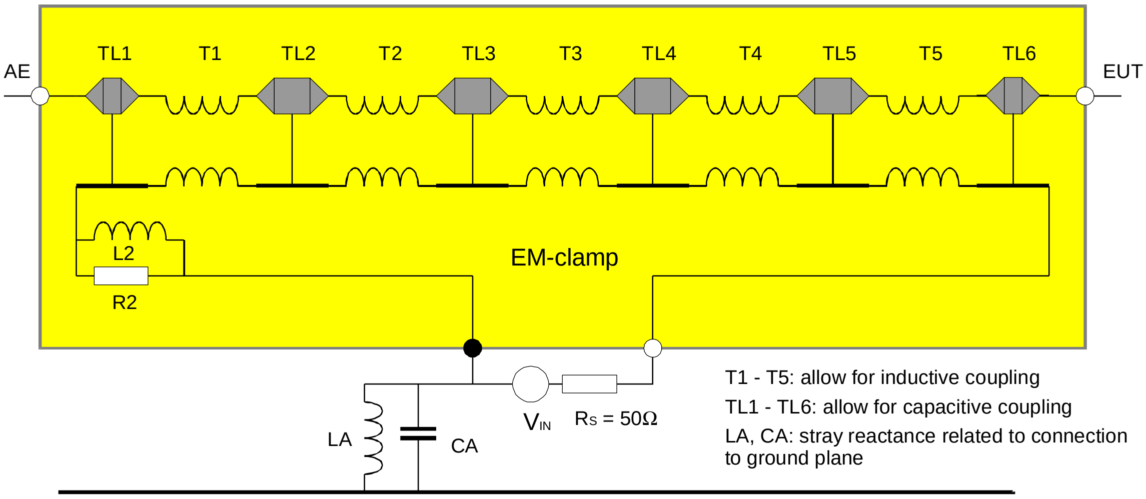

Figure 9 Circuit model of the EM-clamp

2.4.3 Correlation of models with measurements

The models for the transducers were checked by comparing predicted transducer factor and EUT port impedance with those obtained by calibrating the real devices with a network analyser. It has proved generally possible to achieve a match of better than 1dB across the frequency range, with the exception of the EM-clamp where some features of the directivity have not been recreated by the model.

The dummy EUT (see section 2.6.1) has also been compared with its model through network analyser measurements at the input port. Again a good correlation of better than 1dB has been found up to 80MHz; it is clear though that above this frequency the model does not account for all the structural properties in the actual unit.

The total circuit model in fact gives very close correlation with the measurements up to 80MHz. Above this frequency there are marked departures, but the model generally predicts the features of the variations under consideration, even if the exact frequencies and amplitudes differ. This gives a good confidence that the model could be used to predict the impact of other variations if necessary.

2.5 Potential sources of uncertainty

The above description of the circuit model helps to identify possible sources of variation in the applied stress I_{IN}. Essentially, any of the impedances shown in the model affect I_{IN} since it flows through each. The impact of variations in the impedances will be modified by Z_{IN}; it can be expected that a low Z_{IN} will show a different sensitivity to external variations than will a high Z_{IN}.

The actual variations considered in this study are stated in section 2.6.2.

2.5.1 Cable layout

The cable under test forms a transmission line whose characteristic impedance Z_0 depends on its height above the ground plane and its diameter. Height is constrained by the standard to be between 30 and 50mm and this is easily maintained, except near its connection to the EUT. For typical diameters of 4 to 12 mm Z_0 is within the range 140 to 250 ohms (Annex A). The length between the transducer and the EUT is constrained to be between 10 and 30 cm.

For the EM clamp and current injection probe, the cable between the AE and transducer is also significant. This is less constrained; Figure 6 in the standard requires it to be < 0.3m "where possible" but this is clearly only a recommendation and it is often not possible to follow it absolutely.

The untested cables also form transmission lines, limited in length to 10-30cm to their respective CDNs. These transform their terminating impedance of nominally 150Ω to a potentially different impedance at their connection to the EUT, affecting the value of $Z_{CM(EUT)}$.

2.5.2 EUT position

The location of the EUT relative to the ground plane and other metallic objects affects its coupling capacitance and hence the impedance of the EUT structure transmission line. The standard constrains the height to 10cm, which is normally straightforward to achieve. Only minor variations from test to test due to this source are likely.

2.5.3 AE common mode impedance

The CDN is required to maintain its common mode impedance with the AE port short or open circuit. Practical CDNs are able to achieve this requirement easily, and so there is no significant effect from the AE side of the circuit with this method.

This is not the case with either of the clamps. Z_{AE} is an integral part of the circuit when using the current probe, and is only partially decoupled by the EM clamp. Any change in Z_{AE} can be expected to have a significant effect on I_{IN} with either of these methods.

2.5.3.1 Clause 7.2 method

The standard recognises this and in clause 7.2 requires the AE setup to present the 150Ω impedance "as closely as possible". But it is also recognised in clause 6.3 that "it is unrealistic to verify the common mode impedance for each AE setup connected to the EUT". Clause 7.2 gives some specific instructions for achieving the required impedance which is expanded and revised in the draft second edition, but it then goes on to say "in all other cases the procedure given in 7.3 should be followed."

2.5.3.2 Clause 7.3 method

Clause 7.3 states that if the AE CM impedance requirements cannot be met, "it is necessary that the common mode impedance of the AE is less than or equal to the common mode impedance of the EUT port being tested. If not, measures shall be taken ... to satisfy this condition." The applied current is then limited through the use of a secondary monitoring probe to what would occur in a true 150Ω system, that is, double that which occurs in calibration, which is a 300Ω system. The measures to be taken include, as an example, the use of decoupling capacitors at the AE port; but these may induce resonances, and the later draft of the second edition accepts this and proposes instead to use a CDN-M1 or 150Ω resistor.

Yet as noted above, the standard has accepted that it is unrealistic to verify the AE CM impedance. It is also equally unrealistic to verify the EUT port CM impedance. In practice it is not possible to ensure that the common mode impedance of the AE is less than or equal to the common mode impedance of the EUT port. Although the current limiting method ensures against over-testing if the EUT port impedance drops to zero, it would only ensure against under-testing if the AE port impedance was in fact maintained at less than 150Ω. Thus laboratories are left largely without guidance in this crucial aspect of the test, and as a matter of practice it is easy for them to pay insufficient attention to controlling the AE CM impedance as the standard requires.

For this reason, although it is accepted that such practice is strictly speaking not in accordance with the standard, this report has taken variations in Z_{AE} to be a potentially significant contributor to the test uncertainties. We have looked at the situation both when the impedance is maintained within the tolerances allowed in the standard, and when it is not, but takes a value within a range bounded by likely practical extremes.

2.5.4 Transducer variations

The standard does not categorically specify which transducer method to use. Figure 1, "Rules for selecting the injection method", asks the first question "Are CDNs suitable?", to which if the answer is yes they should be used. Criteria for suitability are not defined. From this we may deduce that CDNs are to be preferred but are not mandatory. In the European pre-standard ENV 50141 they were mandatory for all AC and DC power supply cables, but only a recommendation appears in IEC 61000-4-6 (in clause 6.2.2.1).

It must therefore be assumed that if one laboratory decides that for a particular port a CDN is suitable, and uses it, while another does not and uses an EM-clamp, and a third elects for the current injection probe, then the results of all three laboratories are deemed equivalent.

This report therefore looks at the actual equivalence in terms of injected I_{IN} of the three methods.

2.6 Practical measurements

A detailed description of the measurement set-up is given in Annex B.

2.6.1 Dummy EUT

To gain the maximum amount of information in a reasonably efficient manner a dummy EUT was used which gave six settings of input impedance Z_{IN}. Clearly a single dummy cannot represent all likely variations of EUT found in practice, but this design was selected to be typical of medium-sized products, with two cable ports: one is tested, the other is decoupled by a separate CDN and used also to extract the measurement of input current. A diagram of the physical construction and internal circuitry is shown in Figure 10. All variations in test setup were tested in each of the six impedance conditions.

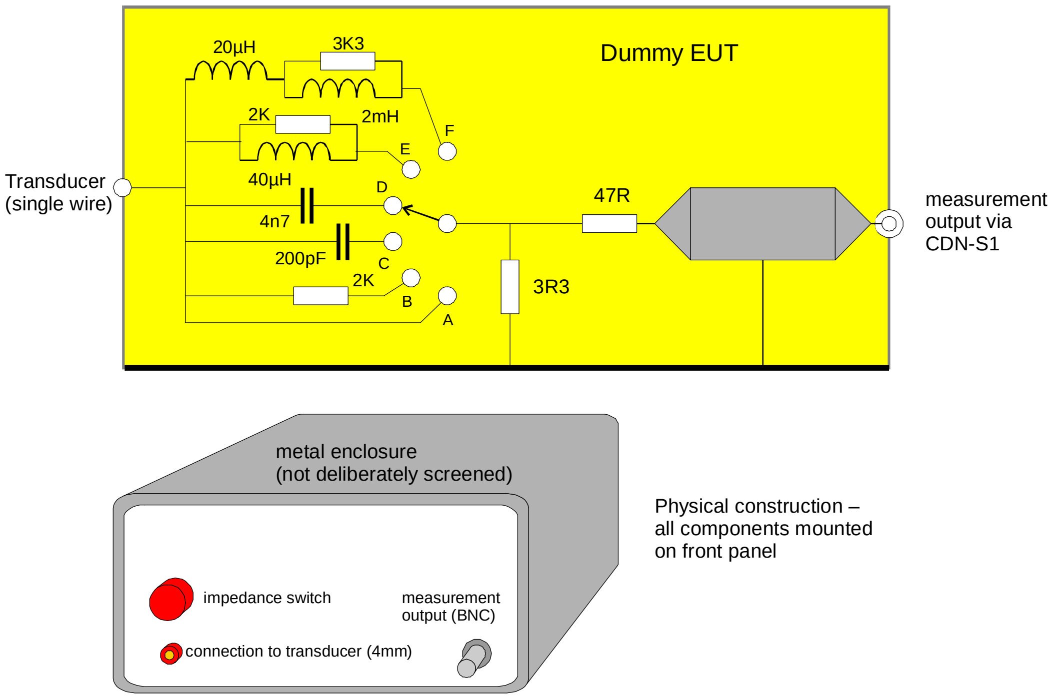

Figure 10 Dummy EUT

The six impedance conditions were chosen to represent either a high or low resistive input, or two combinations of either capacitive or inductive input with values that might be typical of power or signal line ports. In practice, there was little difference over the frequency range of interest between the high impedance resistive input and the higher value inductive input, and between the low impedance resistive input and the higher value capacitive input. Potential resonances between the reactive components at the input and the stray layout reactances did not appear to be significant. Therefore only four of the six conditions were used in analysing the results.

2.6.2 Variations in test setup

Since the purpose of the practical work was to validate the conclusions drawn from modelling regarding the effect of variations, a number of variant conditions were established in the test setup. Figure 11 shows a diagram of the general setup with an indication of those parameters that were varied. The parameters for the untested cable of the dummy EUT (L3, H3 and Z3) were held constant. The table below lists the different conditions that were investigated.

Total no. of tests	Transducer	AE termination Z1	Connection to GP	L2; H2
90	CDN	Open circuit, short circuit, 150R	Direct	L2 = 0.1, 0.3m H2 = 30, 50mm
			Via 5” strap	L2 = 0.1m H2 = 30mm
			Cable position	**L1; L2; H1 & H2**
252	Current injection probe	3R3, 47R, 150R, 470R, 2K, 10pF	Middle	L1 = 0.1, 0.5, 1.0m L2 = 0.1m H = 30, 50mm
			Offset	L1 = 0.5m L2 = 0.1m H = 50mm
			Connection to GP	**L1; L2; H1 & H2**
468	EM Clamp	3R3, 47R, 150R, 470R, 2K, 10pF	Direct	L1 = 0.1, 0.5, 1.0m L2 = 0.1m, 0.3m H = 30, 50mm
			Via 5” strap	L1 = 0.5m L2 = 0.3m H = 50mm

Limits on the length and height above the ground plane (L1, L2, H1, H2) of the cable under test are prescribed within the standard. Variations within these limits were investigated. The CDN and EM-clamp must be bonded to the ground plane, but the manner of doing so is not specified. Both a direct bond and an inductive (5” long) strap were investigated. The current probe may not be centrally located over the cable; the effect of an offset was investigated. Finally, although the standard requires the AE terminating impedance to be maintained at 150 ohms for clamp injection, in practice this is hard to ensure. Variations in this impedance were investigated.

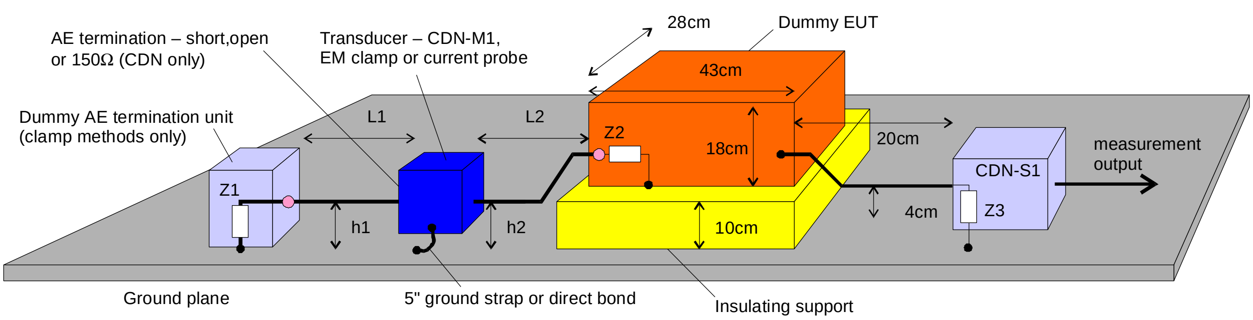

Figure 11 The test setup, showing parameters that were varied

2.7 Results for the CDN

Full graphs of all measurement and modelling for the CDN method are given in Annex C, part 1. The results quoted in the next three sections are segregated by frequency range. The breakpoints for the three ranges (26MHz and 80MHz) are chosen to reflect the observed changes in behaviour of the test in both the model and the measurements. They also coincide with breakpoints implemented in the standard itself. The results for the CDN show that it is undoubtedly the most reliable and repeatable of the three transducers.

2.7.1 Impact of cable layout

With a good ground connection and a Z_{AE} of 150 ohms, the effect of varying the CDN-EUT cable between 0.1 – 0.3m in length and 30 – 50mm height is examined.

2.7.1.1 Frequency range 150kHz – 26MHz

Neither the model nor the measurements show any significant variations in this frequency range, regardless of EUT impedance.

2.7.1.2 Frequency range 26MHz – 80MHz

The model predicts no variation in this range regardless of EUT impedance, but measurements indicated a departure of 3-5dB when the longest cable was raised to 50mm height, for the low impedance EUTs (A and C) only.

2.7.1.3 Frequency range 80 – 230MHz

Both the model and measurements give variations up to 5dB, slightly less for the high impedance EUTs (B and E).

2.7.2 Impact of Z_{AE}

With a good ground connection and the CDN-EUT cable 0.1m long and 30mm high, Z_{AE} is varied between short circuit, 150Ω and open circuit.

2.7.2.1 Frequency range 150kHz – 80MHz

Neither the model nor the measurements show any significant variations in this frequency range, regardless of EUT impedance.

2.7.2.2 Frequency range 80MHz – 230MHz

The model predicts slight variations up to 2dB above 150MHz and these are generally confirmed by the measurement.

2.7.3 Impact of CDN grounding

With the CDN-EUT cable 0.1m long and 30mm high, Z_{AE} is varied between short circuit, 150Ω and open circuit. In the physical measurement the good ground connection is replaced by a thin (0.5mm) insulating layer from the ground plane together with a 5” strap to a stud fixed to the plane. This is represented by 50pF in parallel with a 0.1µH inductance and 1000 ohm resistance in the model.

2.7.3.1 Frequency range 150kHz – 26MHz

Neither the model nor the measurements show any significant variations in this frequency range, regardless of EUT impedance.

2.7.3.2 Frequency range 26MHz – 80MHz

The model predicts a drop in the applied signal at the resonant frequency of the ground strap/CDN capacitance combination, in this case 71MHz. The effect is negligible with a low impedance Z_{AE} , and greatest with an open circuit. A low impedance EUT gives a modelled peak deviation of 10dB while a high impedance EUT gives less, around 6dB. The measurements confirm the effect but without quite such a strong deviation for the worst case situation, suggesting that the Q factor inherent in a 1000 ohm parallel resistance should be reduced somewhat.

2.7.3.3 Frequency range 80MHz – 230MHz

The model gives no suggestion that any further effect is to be expected beyond the resonance of the ground strap, although this effect is seen up to 100MHz. In fact the measurements suggest that a small subsidiary resonance exists at around 170MHz for high-impedance EUTs only which is not accounted for in the model. Total variation that could be expected as a result of the ground strap in this range should be put at around 3dB.

2.8 Results for the EM-clamp

Full graphs of all measurement and modelling for the EM-clamp method are given in Annex C, part 2.

2.8.1 Impact of cable layout

With a good ground connection and a Z_{AE} set to 150 ohms and 2 kilohms, the effect of varying the clamp-EUT cable between 0.1 – 0.3m in length and the clamp-AE cable between 0.1 – 1.0m in length is examined. The height above the ground plane is maintained at 50mm.

2.8.1.1 Frequency range 150kHz – 26MHz

With Z_{AE} set to 150 ohms as advised by the standard, the model predicts negligible layout effect in this range. This is largely confirmed by the measurements although a deviation of about 2dB is noted around 10MHz on only one of the runs (EUT length 0.1m, AE length 0.5m) which is not mirrored in the model results and may be an artefact.

With Z_{AE} set to 2 kilohms (high impedance) there are noticeable departures due to layout over this range, which are accurately replicated in the measurements. Below 1MHz there is negligible effect, but above this deviations up to 2.5dB are found, their exact nature depending on the EUT impedance; a low impedance input gives the higher deviation.

2.8.1.2 Frequency range 26MHz – 80MHz

Increases in variation towards the top of this frequency range are predicted by the model and found in measurement. Greatest deviations are about 5dB for the low impedance EUTs and 3dB for the high impedance. The two different values of Z_{AE} do not greatly affect the maximum level of variation, though they do make a difference to the features.

2.8.1.3 Frequency range 80MHz – 230MHz

The variations noted just below 80MHz continue up to 230MHz. With a 150 ohm Z_{AE} there is little increase in their maximum value but with 2 kilohms some resonant notches are observed in the range 100 – 200MHz. These give a variation up to 10dB and are present on both the model and the measurements although at different frequencies. The model shows a greater effect than the measurements, which may be due to its inadequate representation of damping factors.

2.8.2 Impact of Z_{AE}

With a good ground connection and a clamp-EUT cable of 0.1m, the effect of varying the Z_{AE} between 3.3 ohms and 2 kilohms resistive, and also a pure capacitance of 10pF, is examined. The height above the ground plane is maintained at 50mm. The investigations are performed for three cable lengths between the AE and the clamp, of 0.1m, 0.5m and 1.0m.

2.8.2.1 Frequency range 150kHz – 26MHz

In this range the model and measurement results coincided very closely, except that the depth of certain resonant features around 20MHz differed by about 3dB. The general features of the results were unaffected by the length of AE-side cable. A longer cable emphasised a resonant dip in the profile for Z_{AE} < 150R around 20-30MHz, most noticeably for low-impedance EUTs.

Since the EM-clamp has no directivity in the lower part of this frequency range there is a direct relationship between the induced signal and Z_{AE}, as with the current injection probe. This relationship also depends on the EUT input impedance Z_{IN} and gives the greatest deviation for the lowest Z_{IN}. At the lowest frequency of 150kHz the 10pF capacitive impedance is very high and therefore this value of Z_{AE} invariably gave the lowest input signal, with a maximum deviation from the 150R value of 33dB. For low Z_{AE}, < 150R, the deviation from the 150R value was less than 2dB for high impedance EUTs and less than 5dB for low impedance EUTs. For higher Z_{AE}, up to 2 kilohms, the maximum deviation from the 150R value was 16dB.

2.8.2.2 Frequency range 26MHz – 80MHz

In this range the directivity of the EM-clamp comes into play. The impact of Z_{AE} is not negligible but is much reduced. The length of AE-side cable does affect the resonant dip around 20-30MHz for low impedance EUTs and Z_{AE}, but is otherwise largely irrelevant.

For low impedance EUTs and the maximum AE-side cable length of 1m then the maximum deviations due to Z_{AE} in this frequency range were 10dB. For high impedance EUTs, irrespective of cable length, the maximum deviations were 3dB. The model was rather more optimistic than the measurements in this area.

2.8.2.3 Frequency range 80MHz – 230MHz

At higher frequencies cable length resonances are more significant than variations in Z_{AE}. With the shortest AE-side cable, the model predicts around 6dB maximum variation with Z_{AE}, and this is generally borne out by the measurements. Longer cables create a more pronounced resonant dip around 100-150MHz. At this dip some effect of around 6dB due to Z_{AE} is visible but otherwise the variations are not significant.

2.8.3 Impact of clamp grounding

With the cable 0.3m long on the EUT side and 0.5m long on the AE side, Z_{AE} is varied between 3.3, 150 and 2k ohms. In the physical measurement the good ground connection is replaced by a thin (0.5mm) insulating layer from the ground plane together with a 5” strap to a stud fixed to the plane. This is represented by 50pF in parallel with a 0.1µH inductance and 1000 ohm resistance in the model.

2.8.3.1 Frequency range 150kHz – 26MHz

Neither the model nor the measurements show any significant variations in this frequency range, regardless of EUT impedance.

2.8.3.2 Frequency range 26MHz – 80MHz

The model predicts a drop in the applied signal at the resonant frequency of the ground strap/CDN capacitance combination, which appears around 80MHz. The effect is greatest with a low impedance Z_{AE} , a peak deviation of 20dB being shown for a low impedance and 12dB for a high impedance EUT. A high impedance Z_{AE} shifts the resonant frequency upwards and reduces its amplitude. The measurements confirm the effect but without such a strong deviation, suggesting that the Q factor inherent in a 1000 ohm parallel resistance (included in the model) should be reduced somewhat.

2.8.3.3 Frequency range 80MHz – 230MHz

Away from the resonance there is very little effect of the ground strap other than what might be expected as a result of the increasing inductive impedance. Total variation that could be expected as a result of the ground strap in this range should be put at around 3dB.

2.9 Results for the current injection probe

Full graphs of all measurement and modelling for the current injection probe method are given in Annex C, part 3.

2.9.1 Impact of cable layout

With a good ground connection and a Z_{AE} set to 150 ohms and 2 kilohms, the probe-EUT cable length is set at 0.1m. The effect of varying the probe-AE cable between 0.1 – 1.0m in length with a height above the ground plane of 30 and 50mm for both sides is examined. .

2.9.1.1 Frequency range 150kHz – 26MHz

For a Z_{AE} of 150 ohms, neither the model nor the measurements show any significant variations in this frequency range, regardless of EUT impedance.

A high impedance Z_{AE} (2k) makes a noticeable difference. With a low impedance EUT, varying the cable length creates a variation up to 10dB, beginning from about 2MHz and increasing with frequency. For a given length, changing the height can also make up to 4dB difference. The length effect reduces to around 5dB for high impedance EUTs. The model and the measurements are in close agreement in this frequency range.

2.9.1.2 Frequency range 26MHz – 80MHz

For a Z_{AE} of 150 ohms, the effect of lengthening the cable to 1m is dramatic. The difference between the two shorter cables, irrespective of height, is a maximum of 5dB at 80MHz for the lower impedance EUTs, but this increases to a worst case of 20dB for the long cable and the higher separation. This is indicated by the measurements although the model does not give nearly such large excursions, raising the possibility that a particular mechanism is not accounted for in the model.

For a Z_{AE} of 2k ohms, the deviations noted for the lower frequency range are maintained up to 80MHz. Just above this frequency the 1m cable length creates a large notch which contributes to an increase in deviation at this length; the shorter cables are unaffected.

2.9.1.3 Frequency range 80MHz – 230MHz

The higher Z_{AE} creates a mismatch which causes substantial peaks and troughs in the applied stress throughout this frequency range, the actual frequencies depending on cable length. The maximum deviation is independent of EUT impedance and only slightly affected by cable height. The model indicates a maximum deviation of 30dB which is confirmed by the measurements.

With Z_{AE} of 150 ohms the mismatch is lower as are the excursions. The measurements indicate variations up to 12dB, largely independent of EUT impedance; the model is slightly more optimistic, showing rather less than 10dB.

2.9.2 Impact of Z_{AE}

With a probe-EUT cable of 0.1m, the effect of varying the Z_{AE} between 3.3 ohms and 2 kilohms resistive, and also a pure capacitance of 10pF, is examined. The height above the ground plane is maintained at 50mm. The investigations are performed for three cable lengths between the AE and the probe, of 0.1m, 0.5m and 1.0m.

2.9.2.1 Frequency range 150kHz – 26MHz

In this range the model and measurement results coincided very closely, with the exception of a slight shift in a low-Q resonant feature for EUT E with the 10pF Z_{AE}. The general features of the results were unaffected by the length of AE-side cable.

Since the current injection probe has no directivity there is a direct relationship between the induced signal and Z_{AE}. This relationship also depends on the EUT input impedance Z_{IN} and gives the greatest deviation for the lowest Z_{IN}. At the lowest frequency of 150kHz the 10pF capacitive impedance is very high and therefore this value of Z_{AE} invariably gave the lowest input signal, with a maximum deviation from the 150R value of 40dB. For low Z_{AE}, < 150R, the deviation from the 150R value was less than 2dB for high impedance EUTs and less than 5dB for low impedance EUTs. For higher Z_{AE}, up to 2 kilohms, the maximum deviation from the 150R value was 16dB.

2.9.2.2 Frequency range 26MHz – 80MHz

In this range the impact of Z_{AE} is reduced. The length of AE-side cable is important. The shortest cable does not show resonant behaviour in this frequency range and the maximum variation is about 16dB irrespective of the impedance of the EUT. The 0.5m cable length shows a resonant peak at the top end of the range but the maximum variation remains about 16dB.

When the AE-side cable length is 1m then a resonant notch appears at around 55MHz with Z_{AE} less than 150 ohms. At this notch very high deviations are seen, the model giving up to 40-45dB depth and measurements exceeding 50dB. High values of Z_{AE} did not exhibit a notch until above 80MHz.

2.9.2.3 Frequency range 80MHz – 230MHz

At higher frequencies cable length resonances amplify variations in Z_{AE}. With the shortest AE-side cable, the model predicts up to 15dB variation from Z_{AE} = 150 ohms and the measurements generally confirm this. Longer cables create more pronounced resonant dips and peaks at frequencies depending on the length and resonant mode. At these points the effect due to Z_{AE} variation is found up to 40dB.

2.9.3 Impact of cable offset

In this experiment the cable was routed either directly through the middle of the probe as usual, or offset against the side of the probe housing. The cable was 0.1m at the EUT side and 0.5m at the AE side at a height of 50mm. Three values of Z_{AE} were used, 3R3, 150R and 2k.

2.9.3.1 Frequency range 150kHz – 80MHz

Throughout the whole of this frequency range offsetting the cable made no discernible difference for either the low or the medium values of Z_{AE}. But for a Z_{AE} of 2 kilohms, significant effects were found for all EUT impedances except EUT A, which is the low impedance resistive impedance. In the cases of EUTs B and E (high resistive or inductive impedance) a gradually increasing effect up to 2.5dB at 26MHz was seen; for EUT C (capacitive impedance) the effect was around 6dB at 26MHz. Above 26MHz for each of these EUTs, the effect of the offset was to tune the first resonant peak to a significantly higher frequency. This resulted in effective variations at 80MHz of up to 20dB.

2.9.3.2 Frequency range 80MHz – 230MHz

As with the lower frequency range, no difference was seen for low or medium values of Z_{AE}. For a Z_{AE} of 2 kilohms, the excursions seen below 80MHz were maintained above that frequency, with similar levels (20dB) of variation.

2.10 Comparison of the three transducers

Section 2.5.4 points out that it should be reasonable to expect the same injected stress level for each transducer, all other factors being constant. The measurements and modelling have facilitated a comparison between the three under the various conditions investigated. It is most convenient to break down the analysis into (1) a comparison when Z_{AE} is held to 150Ω as required by the standard, and (2) a comparison when this is not so (implying that the laboratory is not properly following the standard clause 7.2 and without using the safety-net of clause 7.3). The comparison is taken for a reasonably good-practice setup, that is with 0.1m cable transducer-EUT, 0.5m cable transducer-AE, 50mm cable height and good ground connections to the transducers.

Graphs for the two situations for EUT A are shown in Figure 12 and Figure 13; see Annex C for further comparisons.

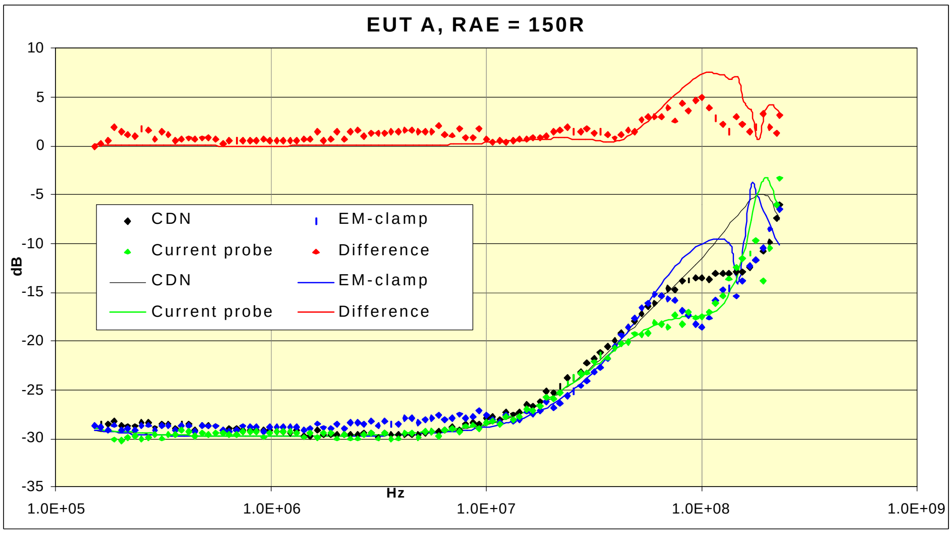

Figure 12 Comparison of transducers for EUT A, Z_{AE} = 150W

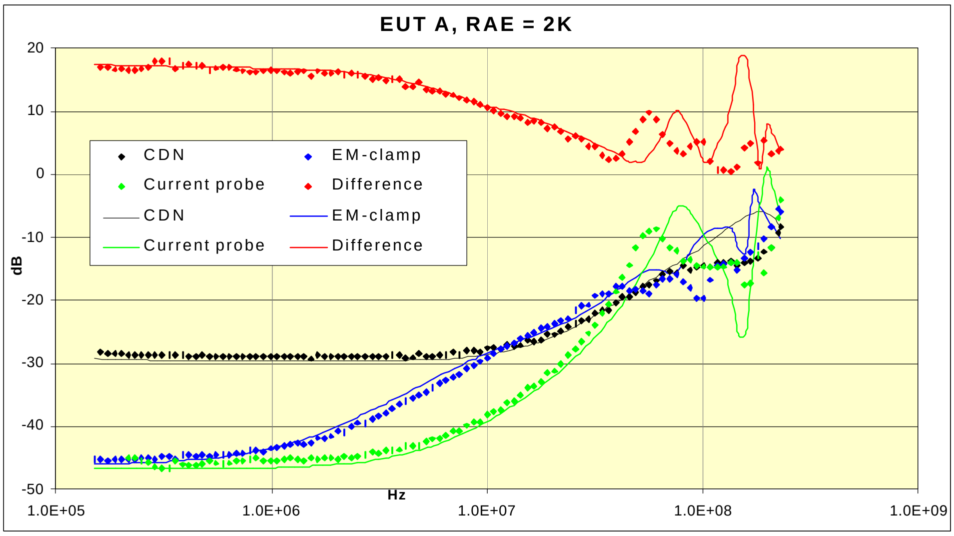

Figure 13 Comparison of transducers for EUT A, Z_{AE} = 2kW

Curves using symbols refer to measurements; solid lines refer to modelled values. Curves marked "Difference" refer to the absolute maximum range of values.

2.10.1 Situation for Z_{AE} = 150Ω (as per the standard clause 7.2)

2.10.1.1 Frequency range 150kHz – 26MHz

In this frequency range the model predicts a difference < 1dB for a low impedance EUT and a slightly higher (1.5dB) difference for a high impedance EUT. An overall difference of 1.5dB is confirmed by the measurements.

2.10.1.2 Frequency range 26 – 80MHz

Here both model and measurements show an increasing variation to around 4dB at 80MHz. Similar deviations although in different senses are seen for both low and high impedance EUTs.

2.10.1.3 Frequency range 80 – 230MHz

Here both the model and the measurements predict variations of 5-10dB.

2.10.2 Situation for Z_{AE} ≠ 150Ω

The implication of this situation is that the conditions in the standard clause 7.2 are not met. Under these conditions the approach of 7.3 should be followed, but as discussed earlier (para. 2.5.3.2) this is difficult to do rigorously.

2.10.2.1 Frequency range 150kHz – 26MHz

As has been pointed out (sections 2.9.2 and 2.8.2), both the current probe and EM-clamp depend critically for their injection level on the AE impedance. Therefore it is no surprise that there are substantial differences between each of these and the CDN method when this impedance is varied. For a low impedance EUT and a high impedance Z_{AE} = 2k, both clamp methods are 18dB lower than the CDN at the bottom end. The EM-clamp approaches the CDN at and above 10MHz but the current injection probe does not. For a high-impedance EUT, the low frequency difference is much less, of the order of 5dB. For a low Z_{AE} the clamp methods are 6dB higher than the CDN up to 10MHz for a low impedance EUT, but only about 2dB higher for a high impedance EUT. The actual differences are clearly related to the interplay between the EUT impedance Z_{IN} and Z_{AE} for the clamp methods. At low frequencies, ignoring the source impedances of the clamps, it is possible to derive a simple expression for the deviation between CDN and clamp results based on these impedances:

$$\frac{i_{in(clamp)}}{i_{in(CDN)}} = \frac{300 + Z_{IN}}{150 + Z_{IN} + Z_{AE}} \qquad \text{(Annex A)}$$

2.10.2.2 Frequency range 26 – 230MHz

Above 26MHz a different pattern emerges. The EM-clamp is now decoupling Z_{AE} from the injection circuit and as a result it follows the CDN curve much more closely. Some deviations are still found where this decoupling is imperfect but these are no worse than 5dB, depending on the relative impedances.

On the other hand the current injection probe gives no such decoupling and we are now in a regime where cable resonances and standing waves are a threat. Both the model and the measurements demonstrate a 20dB peak deviation from the CDN curve for high Z_{AE}, and 30dB for low Z_{AE}. For the 0.5m cable taken in this example the worst deviations are at or above 100MHz, but a longer cable would transfer the problems into the frequency range below 80MHz.

2.11 Other research results

The literature review (section 2.3) refers to two other bodies of work which are directly relevant to this report. Data from this work is summarised here.

2.11.1 Monteyne

2.11.1.1 EM-clamp

Monteyne's work on the EM-clamp and current injection probe (his measurements started at 20MHz and went up to 1GHz) yields the following further observations [9].

- The ground strap has negligible influence on the outcome. This is at odds with our result; however Monteyne apparently left the bottom of the EM-clamp in contact with the ground plane when removing the strap. Under these conditions the strap would indeed have no influence. If the direct contact is not made, then the length of strap becomes much more significant.

- The wire-to-ground plane distance made around 2-3dB difference above 50MHz. This is roughly in accordance with our result.

- The reflected power is a strong function of frequency and wire impedance. This emphasises the necessity of the 6dB attenuator in the IEC 61000-4-6 test since the level control method is based (directly or indirectly) on forward power.

- Above about 40MHz the EM-clamp decouples the AE impedance very effectively.

- The wire diameter has little effect on coupling unless it is small (2.5mm^2, 1.78mm diameter) in which case there is between 2 and 7dB reduction in coupling by comparison with larger wires, above 20MHz. It is not clear though whether this experiment ensured that the wire was closely clamped against the capacitive coupling electrode or whether it was central in the aperture.

- The distance from clamp to EUT makes less than 2dB difference if it is within 20cm; this is consistent with our results. Up to 60cm the deviation increases to 5dB, and up to 140cm the deviation can be 8dB, due to standing waves.

2.11.1.2 Current injection probe

- The reflected power is independent of the wire impedance.

- The current injection probe "can't work properly without a serious decoupling of the AE impedance". The induced signal at the EUT changes by more than 55dB in the worst case. His worst case included shorted and open circuits at the AE end, which is a greater variation than we have used.

- The diameter of the cable under test contributes around 3dB of variation up to 200MHz, as between 2.5mm^2 and 113mm^2 cross section.

- When the AE side is not terminated in 150Ω, a standing wave pattern exists on the cable which can cause the injected signal to vary depending on the distance from the probe to the EUT by up to 35dB, if the distance is varied up to 140cm.

2.11.2 Bersier

Bersier's reports look directly at the influence of the AE impedance and cable layout. He compared the EM-clamp and the current injection probe for different levels of AE impedance and AE-side cable layout, as related to a 150Ω CDN reference setup. A summary of his conclusions from this work [12] regarding use of the current injection probe is as follows:

- The (unconstrained) AE CM impedance can vary within the range 0Ω to 1500Ω, while the EUT CM impedance can vary between 25Ω and 1500Ω.

- It is absolutely necessary to lay out the cable carefully in zigzag (if it is longer than 1m – he used cable lengths between 1m and 12m) at a distance of 3 to 5cm to the GRP; bundles should be avoided, and the length of the cable should be limited to 1m if possible.

- The current injected into the EUT depends very much on the AE side impedance and on the length of cable under test. This current shows very high variations versus frequency when the AE deviates from 150Ω, even with a cable length of 1m. In order to obtain reproducible results it is therefore absolutely necessary to terminate the cable at the AE side with a common mode impedance of 150Ω.

- The application of a ferrite tube at the AE side of the current injection probe cannot be used as a solution for the 5:1 probe because of the high injection power levels that would be needed to apply realistic test levels.

- A reduction of the EUT impedance to 25Ω produces an important additional increase of the error in the whole frequency range. For EUTs with high impedance, the error is reduced at the lower frequencies, but increases at the higher frequencies.

These conclusions are entirely in accord with the results of our own investigations.

2.12 The effect of current probe turns ratio

It has already been observed (section 2.2.3) that the standard uses a 5:1 current injection probe as an example of the method, whereas this ratio is difficult or impossible to obtain commercially and laboratories often use a probe with a 1:1 ratio. One probe manufacturer also offers a 3:1 variant in their price list and it is believed (though not confirmed) that another common type has a 4:1 ratio. This section discusses the effect of the difference in ratios on the test.

2.12.1 Theoretical evaluation

Assuming a unity coupling factor and no losses, the impedance of the primary circuit of any transformer is reflected into the secondary, multiplied by the square of the turns ratio:

$$Z_{\sec} = Z_{prim} \times N^2$$

The primary circuit impedance of the current injection probe is a reasonably accurate 50Ω, set by the 6dB attenuator pad connected to the output impedance of the power amplifier. Thus the secondary impedance, appearing in series with the cable under test by the act of placing the probe around it, will be as shown in the table below. The coupling factor of rather less than 1, found in practice, will serve to somewhat reduce these figures.

Ratio	1:1	3:1	5:1
Z_{sec}	50Ω	5.55Ω	2Ω

This impedance effectively increases the source impedance set by the AE common mode impedance Z_{AE}, which according to the standard is 150Ω. Provided that the calibration is performed in a 150Ω system and Z_{AE} is maintained at 150Ω then the effect of the change in impedance should cancel out. However, Z_{AE} is hard to maintain at 150Ω, as discussed earlier; and in fact clause A.1 of the standard is equivocal about which impedance system should be used for calibration. It would appear that either a 150Ω or a 50Ω system can be used. In the case of a 50Ω system, the effect of Z_{sec} is not properly cancelled by the calibration, and a probe ratio of 1:1 will introduce a substantial fixed error.

The standard requires that the insertion loss in a 50Ω system should be less than 1dB, which translates to a maximum Z_{sec} of 12Ω implying a minimum turns ratio of 2:1 with unity coupling factor. Not all laboratories appear to observe this constraint and it is therefore important to investigate the implications of a lower ratio on the measurement uncertainty.

2.12.2 Modelled results

To show the impact of turns ratio a series of modelling runs were carried out for a current probe with a turns ratio of 1:1, 3:1 and 5:1. Calibration was performed in both a 50Ω and a 150Ω system. The appropriate calibration results were then applied to test runs with the same probe ratios used on EUT A (low impedance) and EUT B (high impedance). The resulting curves of input voltage for the two EUTs are shown in Figure 14. These graphs also carry the curve for a standard CDN test. In all cases a short (0.1m, 30mm high) cable was used to the EUT and for the current injection probes, Z_{AE} was maintained at 150Ω with an AE-side cable length of 0.25m at 30mm height.

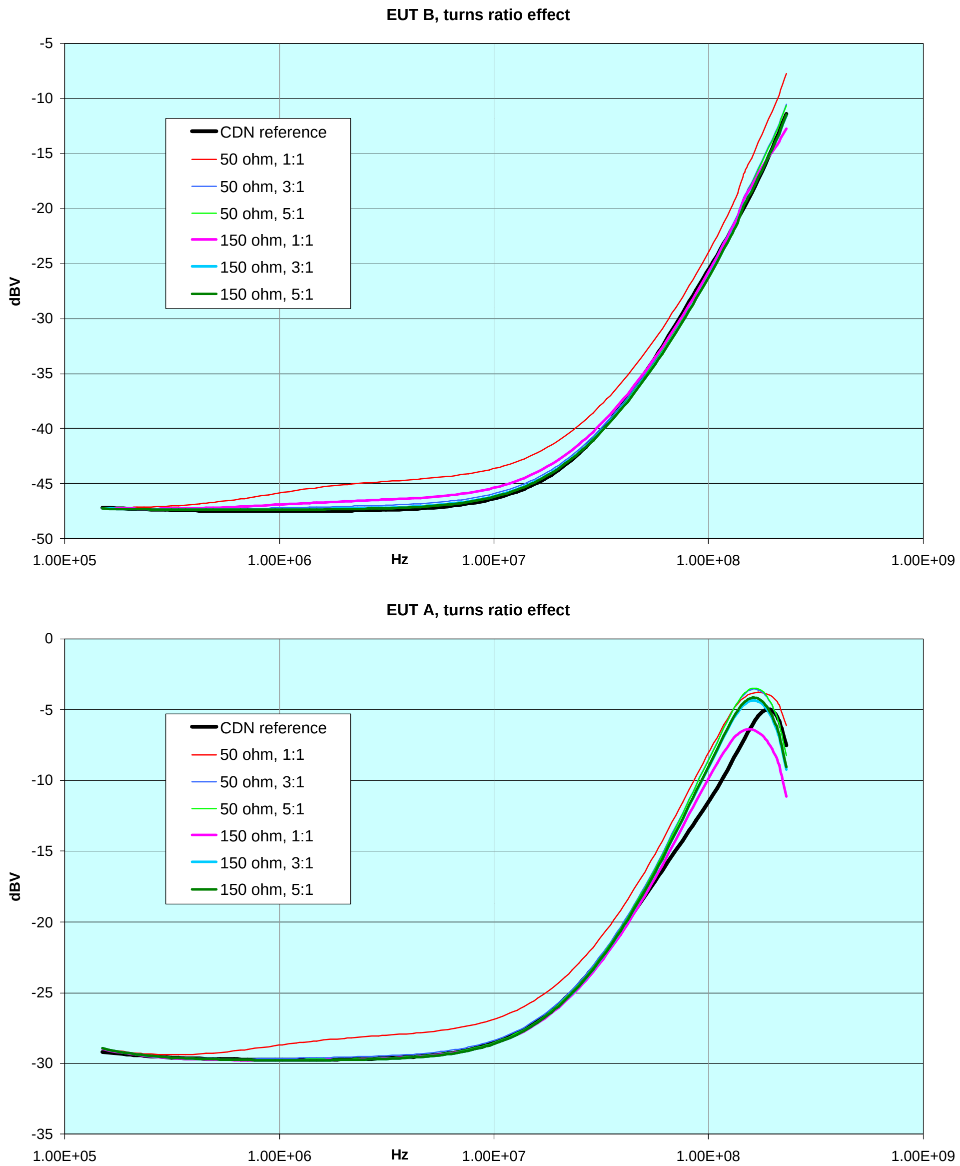

Figure 14 The effect of probe turns ratio for EUTs A and B

These curves show that provided the probe turns ratio is either 3:1 or 5:1 (as required by the standard) then the effect of insertion impedance is negligible, and the probes give good correlation with the CDN method at least up to 80MHz for either EUT. For the 1:1 probe calibrated in a 50Ω system however, there is a systematic increase from the CDN method of 1.5 – 2.5dB above about

2MHz, the frequency at which the probe coupling flattens out to its maximum. The differential is slightly higher for the higher impedance EUT. There is much less differential for the probe when calibrated in a 150Ω system. It is negligible for EUT A (low impedance) and approaches 1dB for EUT B.

This systematic error is easily explained by considering the extra insertion impedance introduced by the 1:1 probe as shown in the table in 2.12.1, which is proportionally greater in the 50Ω system.

2.13 Uncertainty contributions

This section presents our distilled and quantified advice concerning the magnitude of uncertainty contributions to be expected with the different methods.

2.13.1 UKAS LAB 34

LAB 34 [43] gives guidance on the treatment of uncertainties for EMC testing and includes examples for the conducted immunity test. The first example refers to the CDN measurement; a second example relates to the method in which the clamp-injected level is limited by monitoring it with a secondary current probe. Since this report does not address the second method in detail we will refer to the first example only.

LAB 34's example only accounts for the contributions discussed in this report in a general way, under the heading "measurement system repeatability", and refers to this as the standard deviation of a series of repeat readings. It does not consider effects of Z_{AE} for the clamp method. This report expands on measurement system repeatability contribution according to our experiments and findings.

2.13.2 Schaffner guide

Schaffner EMC Systems have also produced a guide to measurement uncertainty [44] which includes typical tables for both CDN and EM-clamp methods. These are reproduced below. As can be seen they include "effects of layout variations" and "effect of AE impedance" as separate contributions.

These two tables give typical values for contributions but each laboratory will need to derive and calculate their own budget.

Conducted immunity measurement 150kHz – 80MHz using CDN							
	Contribution	Value		Prob. dist.	Divisor	$u_i(y)$	$u_i(y)^2$
1	Voltage level monitor	0.40	dB	Normal	2.000	0.200	0.040
2	50-to-150 ohm adaptor	0.10	dB	Rectangular	1.732	0.058	0.003
3	Voltage level setting window	0.50	dB	Rectangular	1.732	0.289	0.083
4	Signal source drift	0.20	dB	Rectangular	1.732	0.115	0.013
5	Amplifier harmonics	0.50	dB	Rectangular	1.732	0.289	0.083
6	Effect of layout variations	0.80	dB	Rectangular	1.732	0.462	0.213
7	Mismatch: CDN to voltage monitor	-1.230	dB	U-shaped	1.414	-0.869	0.756
	Voltmeter VRC	0.20					
	CDN + adaptor VRC	0.66					
8	Mismatch: Amplifier to CDN	-1.160	dB	U-shaped	1.414	-0.820	0.673
	Amplifier VRC	0.50					
	CDN + 6dB attenuator VRC	0.25					
9	Measurement system repeatability	0.50	dB	Normal (1)	1.000	0.500	0.250
						$u_c(y)$	$\sum u_i(y)^2$
10	Combined standard uncertainty		dB	Normal		1.454	2.115
	Expanded uncertainty		dB	Normal, k = 1.64		**2.39**	

Table 2 Typical uncertainty budget for CDN method

Conducted immunity measurement 150kHz – 80MHz using EM-clamp							
	Contribution	Value		Prob. dist.	Divisor	$u_i(y)$	$u_i(y)^2$
1	Voltage level monitor	0.40	dB	Normal	2.000	0.200	0.040
2	50-to-150 ohm adaptor	0.10	dB	Rectangular	1.732	0.058	0.003
3	Voltage level setting window	0.50	dB	Rectangular	1.732	0.289	0.083
4	Signal source drift	0.20	dB	Rectangular	1.732	0.115	0.013
5	Amplifier harmonics	0.70	dB	Rectangular	1.732	0.404	0.163
6	Effect of AE impedance	1.00	dB	Rectangular	1.732	0.577	0.333
7	Effect of layout variations	2.00	dB	Rectangular	1.732	1.155	1.333
8	Mismatch: Clamp to monitor	-1.412	dB	U-shaped	1.414	-0.998	0.996
	Voltmeter VRC	0.20					
	Clamp VRC	0.75					
9	Mismatch: Amplifier to Clamp	-0.819	dB	U-shaped	1.414	-0.579	0.336
	Amplifier VRC	0.50					
	Clamp + 6dB attenuator VRC	0.18					
10	Measurement system repeatability	0.50	dB	Normal (1)	1.000	0.500	0.250
						$u_c(y)$	$\sum u_i(y)^2$
11	Combined standard uncertainty		dB	Normal		1.885	3.552
	Expanded uncertainty		dB	Normal, k = 1.64		**3.09**	

Table 3 Typical uncertainty budget for EM-clamp method

2.13.3 Specific contributions according to this report

This section presents a series of uncertainty contributions which may be expected from a typical test according to our results, taken as far as possible from both modelling and measurement. If there are discrepancies, the measurement takes precedence, especially in situations where the model does not predict a clearly defined feature in the measurements, unless a measurement result is questionable. The contributions are tabulated in the order in which they are presented in sections 2.7 to 2.9. They assume that best practice in layout as recommended in the Best Practice Guide of this project is implemented. Since there is in general no control over the EUT impedance, the worst case EUT impedances have been selected.

The uncertainties are tabulated in ±dB for the three frequency ranges referred to elsewhere. The total (RSS) value is the root-sum-of-squares of the contributions, which may be applied directly in the total uncertainty budget with a rectangular distribution. This assumes that the contributions due to cable layout and Z_{AE} are uncorrelated, which may not be valid in extreme cases for the EM-clamp and current probe.

2.13.3.1 CDN

The following table gives the uncertainties that attach to the CDN method in the face of cable layout variations and extreme variations in Z_{AE} from open to short circuit.

Frequency range	150kHz – 26MHz	26 – 80MHz	80 – 230MHz
Cable layout	0.5	0.6	2.8
Z_{AE}	0.3	0.6	2.2
Total (RSS)	0.6	0.85	3.6

2.13.3.2 Current injection probe: Z_{AE} maintained within specification

This table gives the uncertainties that may be expected if Z_{AE} is held within the specification of Table 1 as required by clause 7.2 of the standard. The Z_{AE} figures are taken only from modelling results as no measurements were taken with Z_{AE} at the specification limits.

Frequency range	150kHz – 26MHz	26 – 80MHz	80 – 230MHz
Cable layout	0.8	5	5
Z_{AE}	1.5	3.7	4.7
Total (RSS)	1.7	6.2	6.9

2.13.3.3 Current injection probe: Z_{AE} outside specification

This table gives the uncertainties that may be expected if Z_{AE} is not held within the specification but extends within the range of 3.3Ω to 2kΩ as considered in this report. The effects due to Z_{AE} mismatch are so extreme for the cable length of 1m that the results for Z_{AE} = 3.3 ohm and L = 1m have been omitted in this presentation. In other words, a low impedance AE is not connected via a long cable, as this is the worst case. Even without the worst case, it can be seen that this combination of circumstances is unacceptable.

Frequency range	150kHz – 26MHz	26 – 80MHz	80 – 230MHz
Cable layout	4.8	8.5	17
Z_{AE}	11	17	18
Total (RSS)	12	19	25

2.13.3.4 EM-clamp: Z_{AE} maintained within specification

This table gives the uncertainties that may be expected if Z_{AE} is held within the specification of Table 1 as required by clause 7.2 of the standard. The Z_{AE} figures are taken only from modelling results as no measurements were taken with Z_{AE} at the specification limits.

Frequency range	150kHz – 26MHz	26 – 80MHz	80 – 230MHz
Cable layout	0.7	2.0	2.8
Z_{AE}	1.0	1.0	2.5
Total (RSS)	1.2	2.3	3.8

2.13.3.5 EM-clamp: Z_{AE} outside specification

This table gives the uncertainties that may be expected if Z_{AE} is not held within the specification but extends within the range of 3.3Ω to 2kΩ as considered in this report. Whilst these values are still too high to represent an acceptably reproducible test, they are noticeably lower than the equivalent values for the current injection probe given in section 2.13.3.3.

Frequency range	150kHz – 26MHz	26 – 80MHz	80 – 230MHz
Cable layout	1.7	2.8	4.1
Z_{AE}	11	5.2	7.5
Total (RSS)	11.1	5.9	8.5

2.14 Conclusions and recommendations

The recommendations we make for tests according to this test standard are expanded in the Best Practice Guide which forms part of the deliverable of this project. The uncertainties which may be attributed to the various factors that have been investigated are quantified in section 2.13.2 above. Our conclusions can be summarised as follows.

2.14.1 CDN method

1. The CDN method is unequivocally more reliable than either of the clamp methods and justifies its choice as the reference method.

2. To ensure minimum uncertainty using the CDN method in the frequency range above 26MHz, each CDN must be directly bonded to the ground reference plane, preferably using immediate metal-to-metal contact and with only a short bonding strap as a secondary means of ensuring the connection.

3. Sensitivity to cable length and layout variations is largely confined to frequencies above 80MHz.

2.14.2 EM-clamp method

1. If the Z_{AE} is maintained at 150Ω the EM-clamp is only slightly more sensitive than the CDN to variations in cable length and layout, both above and below 80MHz.

2. As with the CDN, the ground terminal of the EM-clamp must be directly bonded to the ground reference plane to minimise variations in the range above 26MHz.

3. A large mismatch (high or low impedance) at the AE increases the sensitivity to cable length and layout changes but only to about 4dB for frequencies up to 80MHz, rather more above this.

4. Variations in Z_{AE} from 150Ω are directly correlated to changes in the applied stress below 2MHz, but above this frequency their impact reduces and it is limited to less than 10dB for shorter cable lengths above 10MHz, even extending up to 230MHz.

2.14.3 Current injection probe method

1. If the Z_{AE} is maintained at 150Ω the current probe is only slightly more sensitive than the CDN to variations in cable length and layout, up to 26MHz. Above 26MHz and extending to 230MHz variations in length (up to 1m) and layout can give up to 15dB variation in applied signal.

2. Effects due to cable offset through the probe window are generally negligible unless the AE or EUT have a high impedance.

3. A large mismatch (high or low impedance) at the AE increases the sensitivity to cable length and layout changes to about 10dB for frequencies up to 80MHz, and substantially more above this.

4. Variations in Z_{AE} from 150Ω are directly correlated to changes in the applied stress. This effect persists from 150kHz to 26MHz, above which frequency standing waves on the cable cause larger changes in stress whose amplitude is related to the Z_{AE} deviation and whose frequency is related to tested cable length.

5. The actual turns ratio of the probe has little effect on the test outcome unless it is as low as 1:1 and the probe is calibrated in a 50Ω system, in which case a roughly 2dB systematic error is introduced by comparison with the CDN reference level.

2.14.4 Equivalence of the three methods

1. If the Z_{AE} is maintained accurately at 150Ω then all three transducers give very similar results; the two clamp methods differ from the CDN reference level by less than 2dB over the range up to 26MHz, unless the current probe turns ratio is 1:1 as described above.

2. Any departure from Z_{AE} of 150Ω causes a deviation in the injected stress corresponding to the ratio of the total impedances for each of the clamp methods, but no change for the CDN. The deviation is equivalent for the EM-clamp and current injection probe at low frequencies, but reduces markedly for the EM-clamp at high frequencies.

2.14.5 Short-form recommendations

1. The CDN method is to be preferred in all cases.

2. Proper ground bonding methods should be observed for CDN and EM-clamp.

3. For either clamp method:

   - The requirement to maintain Z_{AE} at 150Ω must be strictly observed, or else section 7.3 in the standard must be properly applied

- cable lengths should be as short as possible, and the total length should be less than 1m
- if longer cables are essential, the EM-clamp method should be used.

4. For all methods, the errors introduced from 80 to 230MHz are very much greater than those below it, and accurate recording of cable layout, length and termination are essential.

5. The current injection probe method in particular is so susceptible to errors from 80 to 230MHz that its use should be prohibited for compliance tests, and only the CDN or EM-clamp methods should be allowed in this range.

6. Any current probe turns ratio greater than 2:1 is acceptable; if a 1:1 ratio probe is used this will not meet the insertion loss requirement, and it may only be calibrated in a 150Ω system, not 50Ω.

3 Radiated Immunity: IEC 61000-4-3

This section discusses uncertainties applying to the radiated RF immunity test. It covers

- field uniformity and chamber performance
- procedures for setting the level
- antenna-to-EUT coupling
- the effects of cable layout.

3.1 A description of the standard

The radiated RF immunity test is defined in IEC 61000-4-3: 2002-3 – referred to as the “current standard” in this report. This is the second edition. The first edition was published as an IEC document in 1995 and by CENELEC as EN 61000-4-3 in 1996. The current version, and Amendment A1 to the first edition, extend the test requirement up to 2GHz; however, for simplicity in this report, only the frequency range up to 1GHz is considered.

An amendment to the current IEC standard has been prepared and in July 2002 was at the FDIS stage (final draft international standard), with the designation 77B/352/FDIS. This document makes substantial changes to the field uniformity calibration procedure, and the closing date for voting was 21st June 2002. The FDIS was published as Amendment A1 to the second edition in August 2002 but for consistency in this report is referred to throughout by its FDIS number. The amendment to the European standard EN 61000-4-3, which is the more important from the perspective of EU implementation, was still in process at the time of writing this report.

Clause 6 of the standard describes the test facility and clause 7 defines the test set-up. Clause 8 is concerned with the test procedures and includes the details of an important pre-test check that should be performed on the test facility. Several aspects of these three sections are relevant to this report.

3.1.1 Calibration of field: Clause 6.2

This section of the standard is concerned with field uniformity and introduces the concept of a "uniform area". The definition of what constitutes a uniform field has remained unchanged in the standards since its original introduction. However, several attempts have been made to define how uniformity measurements are to be used, none of which are entirely satisfactory. The methods described in the current standard and the new FDIS are very different. The method in the current standard may result in the classification of the field as non-uniform in situations where the field satisfies the basic definition of uniformity. The FDIS has the advantage of providing a method that conforms to the definition of a uniform field and is unambiguous. There are alternatives to both methods, one of which is likely to result in smaller differences between different test facilities (see section 3.4.2.4).

3.1.2 Setting the test level

Testing according to IEC 61000-4-3 is a two-stage process referred to as a method of substitution. At each frequency the required field is established in the absence of the EUT using an isotropic field probe and the forward power supplied to the antenna to achieve this field is recorded. As part of this process the uniformity of the field is assessed by establishing the field at several different locations. The immunity test is performed by replaying the power profile with the EUT present.

Since the definition of a uniform field is clear and unambiguous in the standard it is surprising that there have been several attempts to provide methods of verifying the uniformity. These arise from ambiguities associated with setting the test level. If the field over the uniform area were spatially constant, setting the test level would be straightforward. The output of the power amplifier would be adjusted until the required field (e.g. 3V/m) was achieved. The measured field is never uniform, however, and a compromise must be made. If the output of the power amplifier were to be adjusted until the field at the *lowest* field point is at the required level, the field at the highest field point could be up to four or more times the required field in small chambers where the field variation can exceed 12 dB. Choosing another point in the plane at which to establish the required field, as is mandatory in the standards, results by definition in under-testing at some points of the plane.

3.1.3 Test procedures: Clause 8

The test procedures in clause 8 include the following instruction:

> "Before testing, the intensity of the established field strength shall be checked by placing the field sensor at a calibration grid point, and with the field generating antenna and cables in the same positions as used for the calibration, the forward power needed to give the calibrated field strength can be measured. This shall be the same as recorded during calibration. …"

It is an attempt to establish that no change has occurred to the uniformity of the field measured at the calibration stage. As with any measurement set-up small changes can be expected with the passage of time. (Large changes may occur if the configuration of the chamber is changed. This includes changing the antenna, which must be regarded as an integral part of the chamber configuration. The polar patterns of two antennas of the same type can be subtly different even if their antenna factors are similar. In an enclosure such as an anechoic chamber there are many propagation paths from the antenna to the field point in addition to that along the boresite.) This contribution to uncertainties is not discussed in this report, but individual test laboratories should accumulate information relating to their own test facility and update uncertainty budgets on the basis of their findings.

3.1.4 Uncertainty contributions

Because of the major impact of field uniformity, chamber performance and choice of location for test level setting on uncertainties, these topics form a large part of the discussion which follows. They are illustrated in Annex D with measurement results from 44 chambers of varying size and construction which have all been found to meet the uniformity requirements of at least one version of the standard. Apart from the chamber, the commonly recognised uncertainties associated with the measuring equipment – particularly the calibration of the field probe – are not considered in this report. These are generally well understood and have been discussed at length elsewhere [43]. However, the layout of EUT cables is a particular issue which also has serious consequences for the induced stress and this is reviewed at the end of this section.

3.2 Field uniformity

In performing a radiated immunity test the ideal would be to expose the EUT to a field which was completely uniform over an area several times the physical aperture of the EUT. Varying the intensity of the field it would be possible to determine precisely the field level at which the EUT developed a malfunction. The fields encountered in practice are far from uniform even in – or particularly in – the controlled environment of the test laboratory. The definition of what constitutes a uniform field, for measurements according to the standard, is discussed in this sub-section.

3.2.1 The uniform area

IEC 61000-4-3 is concerned with the uniformity of the field over an area measuring 1.5m × 1.5m situated no closer than 0.8m to the earth reference plane. It specifies that, where possible, the EUT should be located at this height. Smaller areas can be used if the EUT and its wires can be fully illuminated within the smaller area. The smallest allowed area is 0.5m × 0.5m. The standard goes on to discuss the requirements that are placed on the field over this area.

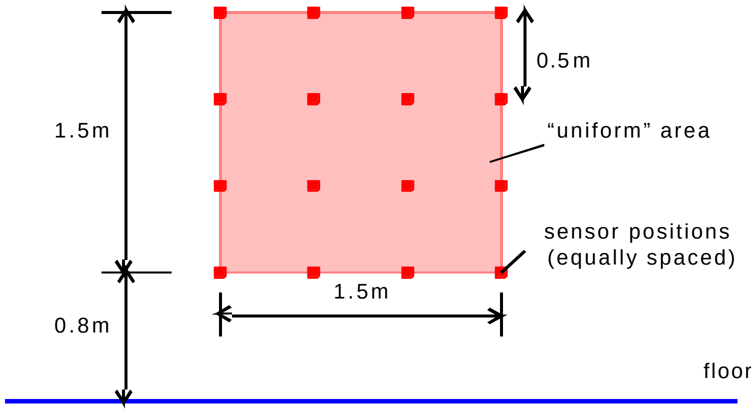

Figure 15 The IEC 61000-4-3 uniform field area

3.2.2 Field variation: incident wave, antenna and ground proximity

For the moment assume that the 1.5m × 1.5m area is located in free space. If a point source (isotropic) antenna is placed in front of the plane it is possible to calculate by simple geometry how far away the source must be in order to obtain a specified uniformity of the field as a result of the curvature of the wavefront. Locating the antenna on the perpendicular through the centre of the area it is easy to show that the source antenna must be at least 10m from the plane area if a field uniformity of better than 0.05 dB (~½%) is required.

To achieve fields in excess of 3V/m high power amplifiers are required and it often becomes prohibitively expensive to test at distances of much more than 3m. The inherent non-uniformity for a separation of 3m between point source and plane area amounts to about 0.5dB. A practical antenna, such as a biconical or log-periodic, located at this distance, will give rise to even larger departures from uniformity due to the non-isotropic polar patterns. For a tuned half-wave dipole the non-uniformity can be calculated (using NEC [42] for example) and amounts to 0.65dB (see Table 10 in section 3.6.1). A similar non-uniformity can be expected for a biconical antenna but the increased focusing of a log-periodic may give rise to larger non-uniformities (probably in the range 1.0 – 1.5 dB).

An additional source of non-uniformity relates to ground proximity. Because of the restrictions on how far it is practical to consider raising an EUT above floor level there are always residual influences due to the proximity of the ground. Above ground all fields have taper; in horizontal polarisation the field strength approaches zero in the vicinity of the ground; in vertical polarisation the field increases as ground is approached. Even in situations where the ground is covered in absorber there is a small taper due to this effect especially at low frequencies.

3.2.3 Field variation: chamber reflections

For the high fields required in immunity testing it is impractical to perform radiated tests in other than sealed enclosures. In both fully anechoic and semi anechoic chambers the field taper due to the proximity of a grounded surface is apparent when field uniformity is measured. It is likely that if all wall and ceiling reflections could be eliminated – by perfect absorber – there would still be an intrinsic non-uniformity of two or three dB due to ground proximity and the other contributions discussed above. High quality absorber in a screened enclosure can reduce reflected fields by as much as 10dB for the predominantly oblique reflections that occur. However, there are so many potential paths from the source antenna to the field measurement point that large variations in the field uniformity are still common. This is due to the constructive and destruction interference that takes place between the fields that propagate via these paths. This is immediately apparent, especially at high frequencies, when the field uniformity data for a chamber is examined where there are large oscillations in the magnitude of the field.

3.2.4 Uniform field: IEC 61000-4-3

The inherently non-uniform nature of the field inside a screened enclosure has been recognised in the standard. The following fundamental definition of a uniform field is given; “A field is considered uniform if its magnitude over the defined area is within –0 dB to +6 dB of the nominal value, over 75% of the surface (e.g. if at least 12 of the 16 points measured are within tolerance).”

The standard goes on to state; “The tolerance has been expressed as –0 dB to +6 dB to ensure that the field strength does not fall below nominal.” This will be true for the 75% or more of the surface included in the 12 or more points. But fields at the remaining points *can be many dB below the nominal value* and it is not clear that this was ever intended since it results in the potential for under-testing.

When the 75% criterion is met there is no limit placed on what may occur at the remaining (up to 4 deleted) points. It will be shown that for small chambers the total field variation can exceed 14dB and yet still meet the 6 dB limit over 75% of the uniform area. The standards committee may not have anticipated this practicality, although it is true that, as long as the deleted points are at the edges of the area, small EUTs that do not encroach on them will not be under-tested.

3.2.5 Measured uniformities

3.2.5.1 Background

Chase EMC (now Schaffner EMC Systems) were unique in 1994 as an accredited EMC test house, an accredited calibration laboratory and a manufacturer and supplier of EMC test equipment. To complement these services Chase added the sales of anechoic chambers and absorbing materials and in order to support these sales it was decided to provide accredited calibrations of Normalised Site Attenuation and Field Uniformity. As there were no other accredited laboratories available this service was provided to screened room and absorber manufacturers around the world and to date well over 100 chambers have been measured internationally which have included traditional pyramidal absorber and/or ferrite tile absorber.

Since mid 1996 many anechoic and semi-anechoic chambers have been assessed for field uniformity. Identification has been removed from this data and it has been analysed for this report. Data are presented for 44 chambers which were measured over the range 80-1000 MHz in 1% frequency steps.

3.2.5.2 Measured chambers

Figure 16 is a plot of the total field variation – that is, the difference between minimum and maximum values – for all 16 points measured in the uniform area in both horizontal and vertical polarisation for all 44 chambers. Figure 17 is a plot of the data for the same chambers restricted to the 12 points having the smallest field variation. The 3 or 4 frequencies at which some of the chambers exceed 6 dB in this plot were deemed to have met the requirements of the standard by virtue of the 3% rule (see section 3.4.2.3). In Annex D the data for the total field variation is plotted in sub-classes of chamber and shows, in particular, the influence of size.

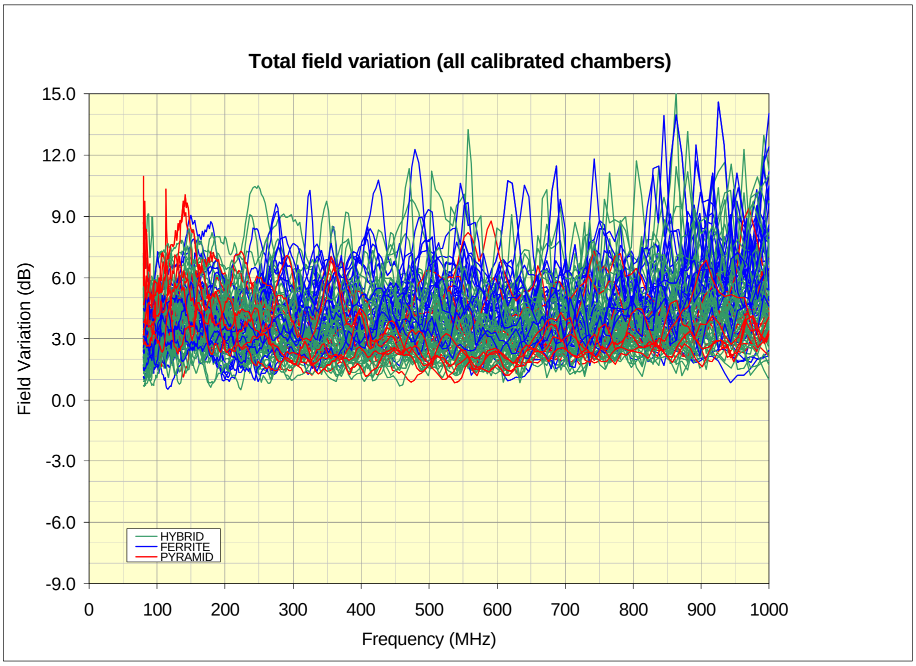

Figure 16 Chamber measurements – total field variation

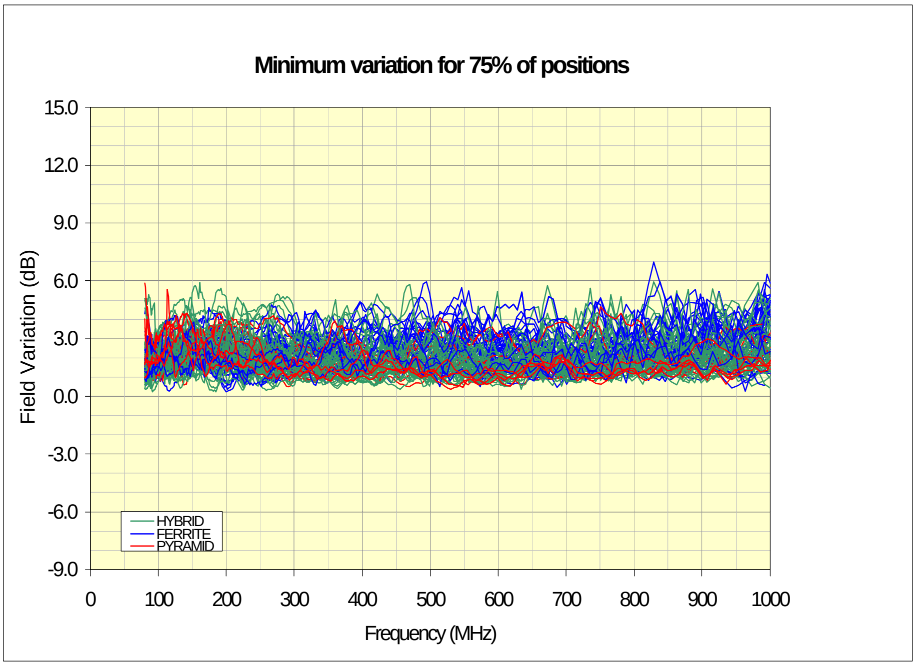

Figure 17 Chamber measurements – 75% of positions

The following features may be observed:

- almost all chambers meet the 6 dB – 75% criterion over the entire frequency range in both polarisations, but
- field variations of up to 15 dB can occur at high frequencies, and
- over the whole frequency range variations in excess of 8 dB occur regularly for most chambers.

These variations will be considered in the contexts of the current and proposed standards.

3.3 Chamber performance

When discussing uncertainties it is useful to have a simple measure of chamber performance. It is possible to define 'quality factors' that relate to the requirements of the various versions of the standards – in particular the current and proposed standards. Although the data is presented in ways relating to the standards the most important factor chosen to distinguish the chambers is independent of the standards and was first used by Dawson et al [20].

3.3.1 Normalised standard deviation, NSD

These authors called their measure of uniformity the normalised standard deviation (NSD). It is evaluated by first computing the mean and standard deviation of all measured fields in V/m (for the 16 field points in both polarisations and for all frequencies). NSD is then defined as follows:

$$\text{NSD} = 20\ \text{Log}_{10}\ (\text{standard deviation / mean})$$

Quoting from the authors' paper:

> "NSD is a negative value in decibels and a value of –20 dBav (decibels relative to the average) would correspond to a typical field variation of 10% i.e. 1 V/m in an average field of 10 V/m. An NSD of $-\infty$ dBav corresponds to a totally uniform field and so the more negative a value of NSD is, the more uniform is the field it describes."

The authors used NSD as a measure of field variation at one frequency. Its use here is extended to generating a quality factor relating to the uniformity measured for all frequencies and both polarisations. The resulting figures for NSD span a similar range to those discussed in [20]. The NSD for all 44 chambers that have been studied is tabulated in Table 4. The chambers are listed in NSD order with the most negative values occurring first. The table also lists the chamber dimensions and volume and the nature of the absorber lining the walls (hybrid, ferrite and pyramidal).

It is clear that, while the best NSD performance can only be obtained with a large chamber, having a large chamber is not by itself a guarantee of good performance. The type of absorber also plays a significant part, and more modern materials (as evidenced by year of calibration) do allow improved performance.

Chamber No.	Year Calibrated	Volume (m^3)	Length (m)	Width (m)	Height (m)	Absorber	FDI (dB)	NSD (dBav)
Class A								
1	2001	557.49	11.36	6.5	7.55	Hybrid	0.014	-18.178
2	2000	297	9	5.5	6	Hybrid	0	-17.702
3	1999	280.8	9	5.2	6	Hybrid	0	-17.656
4	1999	280.8	9	5.2	6	Hybrid	0.003	-17.634
5	1998	291.6	9	5.4	6	Hybrid	0.002	-17.374
6	2001	297	9	5.5	6	Hybrid	0	-17.046
7	2000	280.8	9	5.2	6	Hybrid	0.004	-16.07
Class B								
8	1998	73.78	7	3.1	3.4	Ferrite	0.138	-15.692
9	2001	297	9	5.5	6	Hybrid	0.074	-15.62
10	2000	71.4	7	3	3.4	Ferrite	0.126	-15.548
11	1996	311.01	8.84	5.73	6.14	Pyramid	0.036	-15.48
12	1998	61.39	6.96	2.97	2.97	Hybrid	0.018	-15.297
13	1997	63	7	3	3	Ferrite	0.076	-15.211
14	1999	63	7	3	3	Ferrite	0.073	-14.925
15	1997	63	7	3	3	Hybrid	0.143	-14.888
16	1998	73.78	7	3.1	3.4	Ferrite	0.238	-14.886
17	1996	448.75	12.2	5.49	6.7	Ferrite	0.33	-14.67
18	1999	286.48	8.55	5.52	6.07	Hybrid	0.218	-14.636
19	1997	162	9	4	4.5	Pyramid	0.083	-14.51
Class C								
20	1996	631.01	12.55	6	8.38	Hybrid	0.321	-14.375
21	1998	131.6	8	3.5	4.7	Hybrid	0.253	-14.333
22	1998	325.71	9.4	5.5	6.3	Hybrid	0.313	-14.277
23	1998	392.19	10.37	6.2	6.1	Ferrite	0.142	-14.205
24	1997	331.17	8.9	6.1	6.1	Hybrid	0.279	-14.2
25	1998	106.47	7	3.9	3.9	Pyramid	0.245	-14.067
26	1998	280.8	9	5.2	6	Hybrid	0.45	-13.87
27	1999	88.68	7.14	3	4.14	Ferrite	0.325	-13.751
28	1998	232.46	8.6	5.3	5.1	Hybrid	0.445	-13.568
29	1998	108.95	6.1	4.88	3.66	Hybrid	0.556	-13.49
30	1998	73.78	7	3.1	3.4	Ferrite	0.644	-13.259
31	1999	71.4	7	3	3.4	Hybrid	0.693	-13.054
32	1997	144.57	7.9	3	6.1	Pyramid	0.662	-12.912
33	1998	144	9	3.2	5	Hybrid	0.783	-12.749
34	2001	71.4	7	3	3.4	Ferrite	0.807	-12.697
35	2000	90.72	7.2	3	4.2	Ferrite	0.733	-12.473
36	1999	77.7	7	3	3.7	Ferrite	0.913	-12.465
37	1997	286.18	8.53	5.5	6.1	Pyramid	0.903	-12.26
38	1998	84.12	7	3.05	3.94	Hybrid	1.079	-12.087
39	1999	71.4	7	3	3.4	Hybrid	1.484	-12.052
40	1996	62.35	6.77	3	3.07	Ferrite	1.466	-12.001
41	1997	95.4	8	2.65	4.5	Hybrid	1.228	-11.854
42	1997	63	7	3	3	Ferrite	1.825	-11.115
43	1997	89.67	6.1	3	4.9	Hybrid	1.836	-10.9
44	1997	94.22	7.21	3.62	3.61	Ferrite	2.394	-10.611

The chambers are listed in order of worsening NSD

Table 4 Chamber quality factors expressed as NSD and FDI

3.3.2 Field Deviation Index (FDI)

An additional factor is included in the table that measures the extent to which the field variations exceed 6 dB. This factor we call the Field Deviation Index or FDI and is computed by summing (for all frequencies and both polarisations) the excess which occurs above 6 dB. The index is normalised by dividing by the total number of frequencies (x 2 for polarisation).

$$FDI = \frac{1}{2N_F} \cdot \sum_{excess} \left(\Delta E_{\max} - 6 \right)$$

where ΔE_{max} is the maximum field variation in dB across the 16 points, N_F is the total number of frequencies.

A chamber which has no frequencies at which the field variation exceeds 6 dB has an FDI of 0 dB (variations less than 6dB are ignored), and in a certain sense can be regarded as ideal. There are three such chambers in the sample measured. High quality chambers in general have an FDI lower than 0.02dB. The corresponding figure for the lowest quality chamber in the sample is 2.4dB. This index appears to have a wide range.

3.3.3 Classification

In Annex D and Table 4 the data for the chambers is presented in three classes based on NSD. The first class (Class A) is restricted to the seven chambers with NSD less than –16 dBav. These are all large chambers with hybrid absorber. For these chambers, which may be regarded as high quality, there are only a few frequencies at which the total field variation exceeds 6 dB – FDI is very low. The second class (Class B) consist of a mixture of large and medium sized chambers with various absorber linings which have NSD values between –16 and –14.5 dBav. The last class (Class C) are those chambers with an NSD greater than –14.5 dBav and are mostly, but not exclusively, ‘compact’ (i.e. small) chambers.

Classification	NSD range
A	< –16 dBav
B	–16 to –14.5 dBav
C	> –14.5 dBav

Table 5 Chamber classification

3.4 Field level calibration

The measurand in a radiated immunity test is the electric field intensity, which is actually measured at the field calibration stage. Because it is not possible to create a completely uniform field over the cross-sectional area presented by the EUT this measurand does not have a unique value. It is implicit in the standard that, for many frequencies, there will be at least a 6 dB field strength variation over the uniform area. Since the field is varying with position the nominal test value can, in general, only be established at one position in the plane. In this section the procedures – past and present – for choosing the location in the plane at which to set up the nominal field level are discussed.

3.4.1 Measured points

The following procedure is undertaken at each frequency in 1% steps throughout the tested range. The electric field strength is measured, using an isotropic electric field probe, at 16 positions (see Figure 15) in the uniform area for the same forward power (constant forward power method); alternatively, the forward power required to create the same electric field strength at each location is recorded (constant field strength). In the subsequent processing it is essential that the field measuring probe and power meter are linear. Where the constant forward power method is used the field variation must be restricted to the linear region of the field probe and not allowed to become too low. Electric field probes used on the 10 V/m range for example (when the range can be selected), will generally exhibit more severe non-linear behaviour below 1 V/m. Uncertainties due to this source should be included in the measurement uncertainty budget if relevant but are not discussed further in this report.

To decide whether the field uniformity criterion is met at each frequency the first step is to place the 16 field strengths (or powers) in order of magnitude. It is convenient to regard them as placed in a list with the lowest values occurring first. The extreme field values are now at the extremities of this list. In the first edition of IEC 61000-4-3 (1995-02) section 6.2 contained the following statements:

> "d) Taking all 16 points into consideration, delete a maximum of 25% (i.e. 4 of the 16) of those with the greatest deviation.
>
> e) The remaining points shall lie within ±3 dB.
>
> f) Of the remaining points, take the location with the lowest field strength as reference (this ensures the –0 dB to +6 dB requirement is met).
>
> g) From knowledge of the input power and field strength, the necessary forward power for the required field strength can be calculated."

For many the phrase in d) "with the greatest deviation" was unclear. Deviation from what? Others interpreted this as implying the most deviant field values i.e. those at the beginning and end of the ordered list. Ambiguities arise concerning the field location at which to establish the nominal field.

In an attempt at clarification, an amendment was made early in the standard's history, modifying the first statement: "…of those with the greatest deviation *from the mean value*, expressed in V/m." Unfortunately this introduces potential conflicts with the basic uniformity criterion. In some situations the four points which deviate furthest from the mean can be removed leaving 12 points that do not lie within 6 dB even though 12 (or more) points can be found which *do* lie within 6 dB. An example of this situation is shown in Table 6.

Point no.		Field (V/m)	Field (dB rel. 3V/m)	dB from mean	Deleted
1	U	1.92	-3.88	-4.58	D
2		2.01	-3.48	-4.18	D
3		2.2	-2.69	-3.4	D
4		2.21	-2.65	-3.36	
5		2.42	-1.87	-2.57	
6		2.73	-0.82	-1.52	
7		2.75	-0.76	-1.46	
8		2.99	-0.03	-0.73	
9	R	3.05	0.14	-0.56	
10		3.16	0.45	-0.25	
Mean		3.25	0.7		
11		3.28	0.78	0.07	
12	U	3.46	1.24	0.54	
13		3.66	1.73	1.02	
14		4.3	3.13	2.42	
15		4.65	3.81	3.1	
16		7.26	7.68	6.97	D

Points 1 and 12 (marked U) denote the boundary of the field uniformity criterion, such that 20*Log(3.46/1.92) is <6

Points 1, 2, 3, and 16 are >3dB from the mean and are deleted.

Points 4 to 15 that remain are such that (3.10 – (–3.36)) is >6 dB

Point 9 (marked R) was the reference point set to 3 V/m

Table 6   Example list of field strengths after ordering

3.4.2 Test level

The procedure used for deciding whether or not the 75% criterion was met would be unimportant were it not for the requirement of paragraph (f) above. The nominal field is established at the location of the lowest field point of the 12 or more points that remain. Different choices result in tests at different overall test levels.

Consider the situation where the 16 measured field levels do not lie within 6 dB but removal of either the lowest (first) point or highest (last) point does result in the criterion being met (see Table 7). A choice must be made.

Point no.		Field (V/m)	Field (dB rel. 3V/m)
1		2	-3.52
2		2.62	-1.18
3		2.76	-0.72
4		2.81	-0.57
5		2.81	-0.57
6		2.83	-0.51
7		2.85	-0.45
8		2.9	-0.29
9	R	2.94	-0.18
10		3.17	0.48
11		3.23	0.64
12		3.26	0.72
13		3.27	0.75
14		3.53	1.41
15		3.93	2.35
16		4.72	3.94

Points 1 to 16 have a spread of 7.46 dB.

Points 1 to 15 have a spread of 5.87 dB.

Points 2 to 16 have a spread of 5.12 dB.

1 to 16 cannot be accepted but either 1 to 15 or 2 to 16 can be accepted.

Choosing:

1 to 15 results in no (minimum) under-testing but 1.46 dB of over-testing.

2 to 16 results in no (minimum) over-testing but 2.34 dB of undertesting.

Table 7 Example of test level setting choices

3.4.2.1 Minimum under-testing: 77B/352/FDIS

Where the highest point is rejected and the lowest field value is retained it is at the location of the latter that the nominal field will be set and no field point will be below the nominal field level during testing. This corresponds to the minimum under-testing choice. The field at the highest field point, which has been removed, is unconstrained and may be 12 dB (for example) above the nominal field level.

It is an extreme form of minimum under-testing that forms part of the latest amendment to the current standard (77B/352/FDIS). In this amendment the pairs (1,12), (2,13), (3,14), (4,15), (5,16) are considered in sequence and the first pair with a difference of less than 6 dB is selected. Consider the situation where points 1 (lowest) and 12 lie within 6 dB (Table 8). Here the nominal field will be established at point one regardless of the field at points 13 to 16 all of which may be more than 6 dB above point 1. It might well be that if point 2 were chosen then all of points 2 to 16 might be within 6 dB.

Point no.		Field (V/m)	Field (dB rel. 3V/m)	
1		1.99	-3.57	U’
2		2.49	-1.62	U
3		2.55	-1.41	
4		2.59	-1.28	
5		2.79	-0.63	
6		2.8	-0.6	
7		2.94	-0.18	
8	R	3.07	0.2	
9		3.29	0.8	
10		3.61	1.61	
11		3.92	2.32	
12		3.94	2.37	U’
13		4.23	2.98	
14		4.68	3.86	
15		4.8	4.08	
16		4.83	4.14	U

Points 1 and 12 (marked U’) are within 6 dB and would be accepted by the proposed standard even though all points 13 to 16 lie outside 6 dB.

However, points 2 to 16 (i.e. 15 points) are also within 6 dB.

Choosing 2 as reference would result in 1.95 dB under-test at point 1.

Table 8 Example of minimum under-testing

Minimum under-testing has many attractions. For a high quality chamber it might ensure that at least the nominal field was obtained at all 16 locations at all frequencies. This would appear to be the minimum uncertainty condition but may give rise to substantial differences between different test facilities.

3.4.2.2 Minimum over-testing

This is the opposite of the previous option, as shown in Table 7, where the highest points are retained. It probably corresponds to the highest uncertainty situation. Were this option to be chosen there might be many points in the uniform area which were below the nominal stress level and therefore a high probability of failure to detect a genuine EUT malfunction.

3.4.2.3 From the mean: IEC 61000-4-3:2002-3

The requirement of the current standard is that points are rejected on the basis of their difference from the mean field level. Unfortunately, a point of contention arises. The standard has always contained the paragraph “The remaining points shall lie with ±3 dB”. Prior to any reference to means this paragraph was always considered as equivalent to “The remaining points shall lie within a range of 6 dB”. If this interpretation is retained the majority of chambers meet the requirement of the standard. However, if the paragraph is now interpreted as “The remaining points shall lie within ±3 dB of the mean” a large proportion of chambers which passed according to earlier versions of the standard, now fail. For the processing of the chamber data according to the current standard in this report the more relaxed interpretation has been retained. This allows the majority of cases in which it is known that at least 12 points lie within 6 dB to pass using the current standard. However, as the example in Table 6 shows, this is not always true.

The current standard which implements this method also includes the following statement: “A tolerance greater than +6 dB up to +10 dB but not less than –0 dB is allowed for a maximum of 3% of the test frequencies, provided that the actual tolerance is stated in the test report.” This leads to further inconsistency, for the second choice above, where failures occur for ranges of less than 6 dB! Presumably the statement was introduced in an attempt to allow a small number of non-compliances with the standard but, as seen previously, non-compliance is possible even when 12 or more points lie within 6 dB and therefore meet the fundamental uniformity criterion. This apparent ‘failure’ cannot be included in the 3%. It is certainly desirable that this standard be modified.

3.4.2.4 Minimum test facility variation

For the 1995 version of the standard there is a further choice (one among many) which has attractions. It is possible to select points from the 16 in the plane such that the largest possible area of the plane has a field, during testing, which is within 6 dB of nominal. This choice lies between those of minimum under-testing and over-testing and could be regarded as the choice most likely to result in reproducible results between different test facilities. Although this choice is attractive it does not lead to the smallest uncertainty situation obtained by selecting minimum under-testing.

3.5 Uncertainties caused by field non-uniformity

In this section the under-testing and over-testing of an EUT referred to in sections 3.4.2.1 and 3.4.2.2 above resulting from applying the procedures specified in the current (IEC 61000-4-3: 2002-03) and proposed (77B/352/FDIS) standards are discussed. The data for the three classes of chamber (see section 3.3.3) is examined and summarised. For classes A and B the number of chambers that have been investigated is fairly small so it must be emphasised that the conclusions based on these small samples may not be fully representative. The section ends with a discussion of the uncertainties that are implied as a result of the procedures specified in the standards.

3.5.1 Class A chambers

For the seven chambers in this class the field variation (i.e. maximum non-uniformity) is less than 8 dB for the entire range of frequencies. There are five excursions over 6 dB all but one of which are for different chambers. Three chambers have zero FDI (see section 3.3.2).

IEC 61000-4-3: 2002-03: No over-testing occurs. Under-testing of 1 dB is common throughout the frequency range and the under-testing peaks at about 3 dB. The 1 dB of under-testing even occurs for the chambers with FDI of zero where all 16 points meet the 6 dB field uniformity criterion over the whole range of frequencies. This is a consequence of deleting points that are more than 3 dB from the mean field value. If the standard stated that where the total spread for all 16 points was less than 6 dB the sifting procedure was not to be used the under-testing would not occur. But the standard does not acknowledge that you can know – in advance – whether the complete range is less than 6 dB!

77B/352/FDIS: For one chamber under-testing of about 1 dB occurs at one frequency. Over-testing is also limited to 1 dB

3.5.2 Class B chambers

The maximum field variation for the twelve chambers in this class is 11 dB, with only three chambers having excursions of more than 10 dB. The field variation is mostly less than 8 dB below 900 MHz.

IEC 61000-4-3: 2002-03: There is very little over-testing and under-testing is limited to about 4 dB up to 800 MHz. Above this frequency under-testing rises to 6 dB. Over almost the entire frequency range there is under-testing of at least 1 dB.

77B/352/FDIS: Over-testing of up to 3 dB takes place. Below 800 MHz the under-testing is limited to 3 dB but above this frequency it increases to about 6 dB at some frequencies.

3.5.3 Class C chambers

The field variation peaks at 15 dB with several excursions greater than 12 dB.

IEC 61000-4-3: 2002-03: Over-testing of 3 dB occurs at one frequency but it is mostly limited to 1 dB. Under-testing of up to 8 dB occurs below 800 MHz and rises to 10 dB above this frequency.

77B/352/FDIS: Over-testing to about 3 dB occurs but is mostly below 2 dB. Under-testing up to 8 dB is common over the whole range of frequencies.

3.5.4 Uncertainties associated with under-testing

Under-testing must be regarded as introducing an uncertainty since part of the surface of the EUT is exposed to a field that is below the requirements of the product standard. (Some might argue that since the procedures of the basic standards have been followed this should not be considered an uncertainty. However, what is uncertain is whether the EUT would operate correctly if exposed to the field specified in the product standard over its entire surface. The concern here is with the uncertainty of the field, not the EUT's response.)

Over-testing introduces a different problem. If an EUT that is subjected to over-testing shows no malfunction over the entire frequency range, no additional uncertainty in its response due to field variations is introduced. However, if failures occur it could be a consequence of over-testing and may result in unnecessary, and possibly expensive, modifications to the EUT in order to secure a pass. Over-testing is an inevitable consequence of using lower quality chambers but, of itself, does not lead to increased uncertainties.

Under-testing is a more severe problem. As the above analysis has shown, if the procedures described in the standards are followed there are nearly always some frequencies at which part of the uniform area has fields below the nominal field. This could result in a failure to detect a genuine malfunction of an EUT, in other words a spurious pass. Different chambers will exhibit different frequencies at which this occurs and therefore there is an uncertainty associated with the result from chamber to chamber.

If the frequency range from 80 MHz to 1000 MHz is traversed in 1% frequency steps (a logarithmic scan) testing occurs at 255 frequencies. An EUT may be such as to fail, if subjected to the nominal field over its entire area, at any one (or more) of these frequencies. If under-testing takes place at (say) one of these frequencies there is a small probability that a genuine failure may be missed. Based on the number of frequency steps alone this probability would be 1/255. At most 25% of the uniform area can have a field below the nominal field. This introduces an additional factor of ¼ into the probability calculation since the EUT must lie within this area and may respond to stimulation over any part of its surface. In this example the probability of missing a failure is very low.

The prospect of application of an unintentionally low field should certainly be included as an uncertainty. Table 9 summarises the magnitude of this uncertainty, omitting the above statistical aspect, for the three classes and two standards:

Chamber	IEC 61000-4-3: 2002-03		77B/352/FDIS	
	(80-800 MHz)	(800-1000 MHz)	(80-800 MHz)	(800-1000 MHz)
Class A	2 dB	2.5 dB	0 dB	1 dB
Class B	3.5 dB	6 dB	2.5 dB	6 dB
Class C	7.5 dB	10 dB	7.5 dB	9 dB

Table 9 Under-testing uncertainties versus chamber class

These uncertainties appear to be significant but can be avoided altogether by departing from the procedures described in the standards. If the lowest-field point is always set to the nominal field there is no under-testing. The over-testing (applying fields outside the –0 to +6 dB range) in this situation is limited to 2 dB for a class A chamber, 4 dB for a class B chamber and 9 dB for a class C chamber. An EUT which passes (i.e. shows no malfunctions) with this procedure must, of necessity, pass when subjected to the procedure in the standard (assuming that the EUT does not exhibit a "window" of susceptibility). If an EUT fails with this procedure the test could be performed again using the procedure in the standard. If this results in a pass an ambiguous situation arises since it is not known whether the failures are a consequence of over-testing or are genuine. Risk assessment will be required if this occurs!

It is strongly recommended that users become familiar with the 'profiles' of their chambers and are aware of the particular frequencies at which under-testing takes place. For this situation it is not necessary to use the 'global' uncertainties given in Table 9 but to use the measured lower field limit to calculate the uncertainty. If the uncertainties in the table are to be used the NSD needs to be known in order to determine the chamber class.

KNOW YOUR CHAMBER!

3.6 Uncertainties due to antenna-EUT coupling

Field uniformity is measured in the absence of the EUT. It is often erroneously stated that the field uniformity of relevance for immunity testing is completely destroyed when the EUT is placed in front of the antenna. The total field in the chamber is certainly much less uniform after the EUT has been introduced since currents are induced in the metal parts of the EUT and these act as secondary sources of electric field. However, if the currents on the antenna are unchanged (in magnitude and phase over the entire antenna) in the presence of the EUT the component of the field created by the antenna is unchanged and it is this field to which the EUT is exposed. (This is a consequence of the superposition principle of electromagnetic field theory, which originates from the linear nature of the field equations.)

On the other hand, the currents on the antenna will change if there is significant coupling between the EUT and the antenna and it is this coupling that is considered in this section. At the lower frequency limit of 80 MHz the wavelength is 3.75m. The EUT is situated 3m from the (tip of the) antenna and for the lowest frequencies of interest there is the potential for significant antenna-EUT coupling (near field effects can be expected if, for a biconical antenna, the EUT-antenna separation is less than about $\lambda/2\pi$ = 0.6m at 80 MHz). This has been investigated both numerically and experimentally.

3.6.1 Antenna-antenna coupling

Since in many situations the EUT acts as a secondary coupled antenna, the first situation to be studied consisted of an 80 MHz tuned, half-wave dipole with a similar shorted dipole placed 3m away in parallel – see Figure 18. The source antenna was supplied from a 50-ohm voltage source.

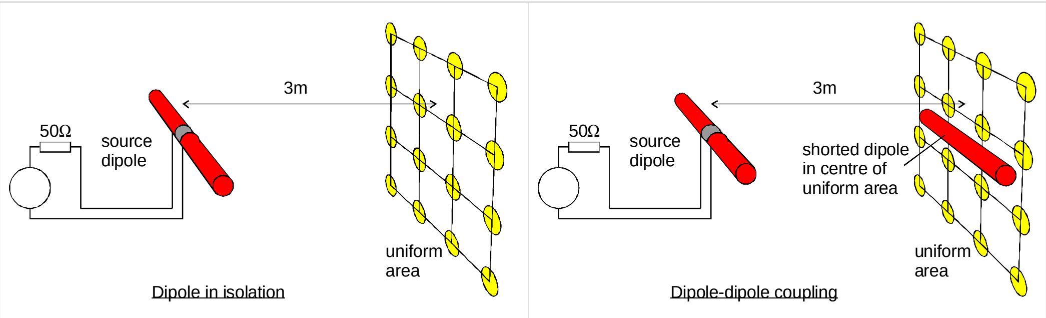

Figure 18 Geometry of modelled coupling

This arrangement can be easily modelled using NEC [42] and the currents and fields determined in the two conditions of interest: (1) with the source antenna in free space – closely resembling the empty chamber – (2) with the coupled antenna present – representing the EUT. In NEC two dipoles are treated as a single radiating structure (rather like a primitive yagi antenna) and there is no facility to calculate the field due to a subset of the structure. This means that, in the second case, although the total field can be calculated (and this is of interest) the field due to the 'source' antenna alone cannot be determined. (For the coupled antennas both are radiating but the field sourced by the driven antenna is required.)

To get round this limitation a small program was written which used exactly the same methods as NEC for wire antennas, and this was used to determine the fields in this situation. All calculated currents were cross-checked with NEC. The results are shown in Table 10. For convenience all fields have been normalised to the calculated field at the centre of the 1.5m x 1.5m plane for the free-space situation and expressed in dB.

11			**12**			
-0.73	-0.13	-0.86	-0.54	-0.12	-0.66	→
	-3.41			+9.88		
21			**22**			
-0.30	-0.13	-0.43	-0.09	-0.13	-0.22	→
	-6.06			+16.86		
	↓			↓		

Table 10 Changes due to antenna-antenna coupling

Notes: all figures are field values in dB relative to the field at the centre of the uniform area with only one dipole present. Each main cell refers to one point in the plane labelled as a matrix: 11, 12, 13, 14, 21, 22.. etc. Only one quadrant of the total 16 points is given, the other points are symmetrical reflections.

The blue figures are the field due to the source dipole in isolation

The red figures are the field due to the source dipole with the second dipole (representing the EUT) present

The green figures are the change in the source dipole field due to the introduction of the second dipole

The grey figures are the total field in the plane (in which the second dipole is located)

3.6.1.1 Coupling changes

Due to the coupling the contribution to the total field generated by the source antenna has changed by about 0.13 dB. To within 0.01 dB the change is the same for all 16 field points. For this coupled pair one may assume that – to first order – the field uniformity is unchanged but the magnitude of the field has reduced by approximately 0.13 dB.

3.6.2 Antenna-image coupling

The second arrangement to be analysed numerically was of a tuned half-wave dipole placed 3m from a conducting metal sheet of infinite extent. The coupling here is with the image in the metal sheet, this image being located 6m from the source antenna. Although the image is 3m further away than the coupled antenna in the previous example the current in the image is identical to that in the source antenna. The NEC derivative program was used to calculate the fields in this situation. The component of the total field that lies in the plane of the sheet is zero (boundary condition), but it is the field due to the source antenna that is of interest not the total field created by the source and its image. The results are shown in Table 11 with the same normalisation as before.

11			**12**			
-0.73	-0.73	-1.46	-0.54	-0.72	-1.26	→
21			**22**			
-0.30	-0.73	-1.03	-0.09	-0.73	-0.82	→
	↓			↓		

Table 11 Changes due to antenna-image coupling

Notes: all figures are field values in dB relative to the field at the centre of the uniform area in the absence of the conducting sheet. Each main cell refers to one point in the plane labelled as a matrix: 11, 12, 13, 14, 21, 22.. etc. Only one quadrant of the total 16 points is given, the other points are symmetrical reflections.

The blue figures are the field due to the source dipole in isolation

The red figures are the field due to the source dipole with infinite conducting sheet present

The green figures are the change in the source dipole field due to the introduction of the conducting sheet

3.6.2.1 Coupling changes

The change in the field over the entire plane area is about 0.73 dB. To within 0.01 dB the field uniformity is unchanged. The total field is not shown in the figure since, as mentioned above, it is very nearly zero in this situation. The ‘EUT’ has had a major effect on the total field (and its uniformity) but not on the uniformity of the external field to which it is exposed!

3.6.3 Experimental measurements

A 90 MHz tuned, half-wave dipole with balun was measured over the frequency range 80 –200 MHz over a ground plane on an open area test site. The antenna was first placed 4m above the ground plane and oriented in vertical polarisation to simulate the free-space (empty chamber) situation. It is known that there is only small coupling to the ground plane in this situation [21]. In an anechoic chamber there would probably be slightly greater coupling to the (six) absorber lined walls. It was then mounted 3m above the ground plane in horizontal polarisation to simulate the presence of a large metal EUT – see Figure 19.

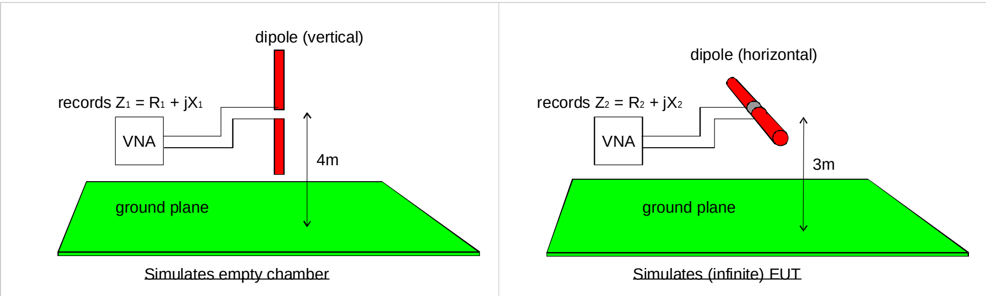

Figure 19 Geometries for investigation of EUT coupling effects

Fairly obviously, fields cannot be measured, and as an alternative the change in the antenna input current amplitude was determined. (It is assumed in this discussion that the current distribution is unchanged.) Since the 50-ohm source was the same for both orientations it was only necessary to measure the antenna input impedance with a VNA. From the measured values of $Z_{in} = R_{in} + j X_{in}$ in the two arrangements it is possible to determine the change in antenna current in dB. Since the field from the source is directly proportional to the current this gives the change in electric field in dB. The resulting change in ‘field’ is shown in Figure 20(a). A similar measurement using a biconical antenna over the frequency range 80 – 200 MHz is shown in Figure 20(b).

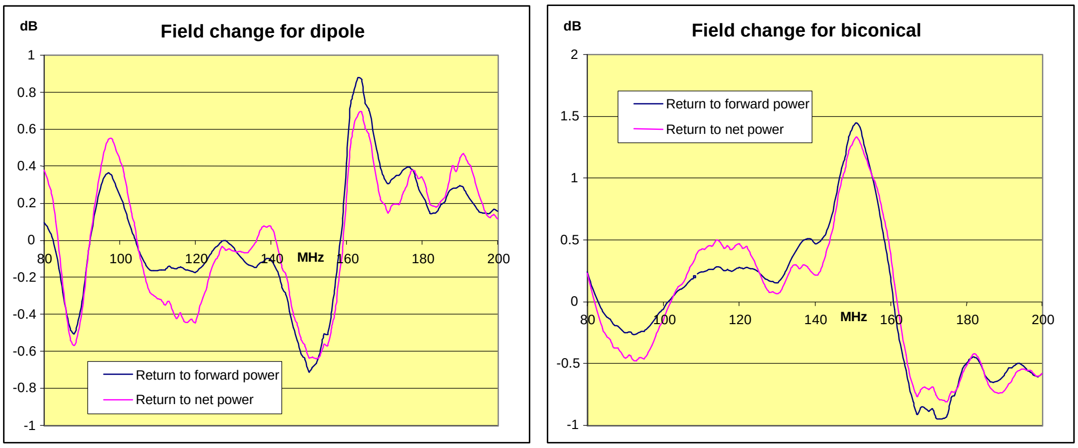

Figure 20 Antenna-EUT coupling effect for dipole (a) and biconical (b)

3.6.3.1 Coupling changes

For the rather extreme case of a very large conducting EUT the maximum field change observed in these two examples is 1.4 dB. This is the situation when there is a return, during testing, to the same forward power (as required by the standards). If a return to net power is used the largest changes are slightly reduced (~0.2 dB). These changes are at their greatest around 160 MHz where the separation-to-wavelength ratio is becoming relatively large. A similar study with a finite, ungrounded metal sheet of dimension 1m x 2m as an EUT resulted in reduced changes that were all less than 0.6 dB.

3.6.4 Summary of coupling uncertainties

For a starting frequency of 80 MHz it seems likely that the presence of the EUT does not appreciably disturb the *field uniformity* of the superimposed field (changes less than 0.01 dB). However, the *magnitude* of the field can change by up to 1.4 dB (in the extreme case studied). For the majority of 'finite' EUTs the change in field magnitude is not anticipated to exceed 1 dB.

3.7 Uncertainties associated with cable layout

Irrespective of the uniformity and level of the field, some variations will occur for EUTs with connected cables, because of the variable layout, length and termination of the cables. The field couples with the cables as well as with the EUT, and induces a common mode current at the connection ports in the same way as occurs in the conducted test described in section 2 of this report. The geometry of each cable will determine the field coupling and hence the magnitude of the induced current.

3.7.1 Requirements of the standard

3.7.1.1 Standard wording

IEC 61000-4-3 places some constraints on the cable layout. Clause 7 includes the following instructions:

> "… Wiring shall be consistent with the manufacturer's recommended procedures …
>
> … The equipment is then connected to power and signal wires according to relevant installation instructions.
>
> **7.3 Arrangement of wiring**
>
> If the wiring to and from the EUT is not specified, unshielded parallel conductors shall be used.

Wiring is left exposed to the electromagnetic field for a distance of 1m from the EUT.

Wiring between enclosures of the EUT shall be treated as follows:

- the manufacturer's specified wiring types and connectors shall be used;
- if the manufacturer's specification requires a wiring length of less than or equal to 3 m, then the specified length shall be used. The wiring shall be bundled low-inductively to 1m length;
- if the specified length is greater than 3 m, or is not specified, then the illuminated length shall be 1m. The remainder is decoupled, for instance via lossy r.f. ferrite tubes.

The EMI filtering used shall not impair the operation of the EUT. The method used shall be recorded in the test report.

In one EUT position, the wires shall be arranged parallel to the uniform area of the field to minimize immunity.

All results shall be accompanied by a complete description of the wiring and equipment position and orientation so that results can be repeated.

The bundled length of exposed wiring is run in a configuration which essentially simulates normal wiring; that is, the wiring is run to the side of the EUT, then either up or down as specified in the installation instructions. The horizontal/vertical arrangement helps to ensure worst-case conditions."

3.7.1.2 Unresolved issues

These instructions are mostly helpful but still leave many questions open, particularly regarding the termination of the far end of each cable. Frequently a cable must be passed through the chamber wall or floor, at which point it may be bonded, filtered or decoupled to the chamber, or passed through with no connection, or passed via a ferrite clamp. No guidance is given as to which method to prefer, yet the source impedance at the EUT port will differ dramatically depending on which is used.

A related question is the interpretation of the phrase "Wiring is left exposed to the electromagnetic field for a distance of 1m from the EUT". How is wiring suddenly switched from being exposed to being un-exposed at a distance of 1m? And what, indeed, is meant by "exposed to the field"? It is clear, for instance, that the field does not suddenly vanish at the edges of the uniform area but tapers towards the floor and sides of the chamber. The technical opacity of this instruction allows laboratories to make a wide variety of interpretations.

3.7.2 Investigations

3.7.2.1 Description of the setup

To quantify the effect of these interpretations a short investigation was performed with a dummy EUT and cables, to find the range of variations with simple changes in cable layout and termination. The actual layout and description of the measurements can be found in Annex E. The EUT was a small metal box with a 1m length of single-core wire connected via a resistor to the case; the voltage across this resistor was passed via a second screened cable through a termination at the chamber floor to a measuring device. The screened cable could be length 1m or 2m and terminated directly or via a CDN-S1, and the single core wire could be left open, or connected either directly or via a CDN-M1 to the chamber floor. All of these configurations except the 2m exposed length of the screened cable are consistent with the specifications in IEC 61000-4-3.

3.7.2.2 Results

The results of these measurements in terms of induced voltage for a field of 3V/m are shown in short form here and in more detail in Annex E. The groups of four curves of each colour show variations in the screened cable length and termination, and the data are coded as follows:

red line	Single wire: horizontal, open circuit
purple line	Single wire: vertical, open circuit
cyan line	Single wire: vertical, CDN termination
green line	Single wire: vertical, short circuit
thick blue line	Spread of all 16 measurements
dotted blue line	Average of spread

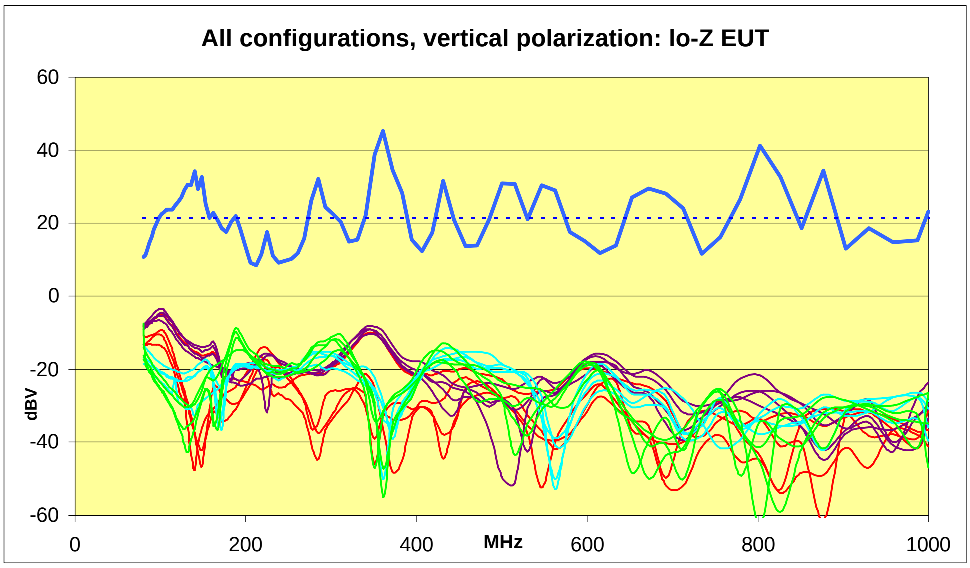

Figure 21 Variations of induced stress with respect to cable layout – vertical polarization

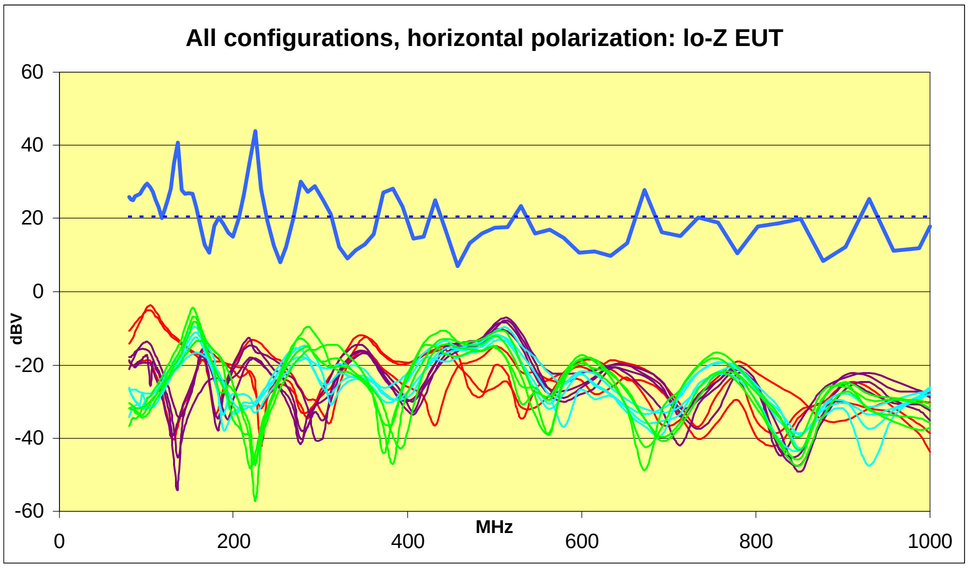

Figure 22 Variations of induced stress with respect to cable layout – horizontal polarization

3.7.2.3 Discussion

The data are presented separately for horizontal and vertical polarization. Although some patterns are discernible with respect to the interactions of the two cables and their terminations, the clearest message from these figures is the substantial range of variations that can be found even with this simple setup. The maximum deviation that can be found, staying within the instructions in the standard, is shown separately on the graphs. Clearly the maxima are related to the resonant lengths of the cables. The deviation peaks at over 40dB and averages around 21dB for both vertical and horizontal over the frequency range. Horizontal polarization appears to be slightly better than vertical above 300MHz and slightly worse below it, though this may not be a universal feature.

A tentative observation is that cables terminated by a CDN appear to remain mostly within the centre of the observed range and do not exhibit the extremes of either a short or open circuit.

Variables such as EUT size and port impedance, and other cable configurations, will also contribute to these variations, but it is felt that the results presented here are not at all untypical of actual variations found in practice. A more in-depth analysis with different EUTs and modelling of the field coupling is recommended to give a greater confidence in the spread that might be expected.

3.7.2.4 Uncertainties

From the above discussion, we suggest that the figure that can realistically be expected for uncertainty in applied stress due to cable configuration, if the test configuration is uncontrolled except by the text of the standard, is of the order of 20dB. This figure evidently dwarfs all other uncertainties. For this reason, we feel it is at least imperative that the test report states clearly the actual configuration tested, as required by the standard:

> All results shall be accompanied by a complete description of the wiring and equipment position and orientation so that results can be repeated.

A “complete description” must include the length, exact layout and termination method for each cable in the setup.

3.8 Conclusions

1. The chamber construction makes an appreciable difference to the range of field values and it is helpful to have a quality factor to describe this range. We discuss the generation of such a quality factor (the NSD).

2. Using the NSD, the likely uncertainties due to under-testing because of field non-uniformity can be estimated for a given chamber. Alternatively, a more accurate assessment can be derived from actual field uniformity figures.

3. The method proposed in 77B/352/FDIS is a substantial improvement on the previous standard and should be adopted as quickly as possible.

4. Uncertainties due to antenna-to-EUT coupling have been found to approach 1.5 dB. At closer distances than 3m a higher value should be expected.

5. Uncertainties due to cable layout variations that are not controlled within the standard method may be of the order of 20dB or greater. To deal with this source, the test report must state clearly the actual configuration tested, including the length, exact layout and termination method for each cable. It may be preferable to terminate cables with an appropriate CDN to the chamber wall or floor rather than leave them short- or open-circuit.

4 Effects on the EUT performance

4.1 Introduction

The previous sections of this report have discussed the uncertainty of the *level of stress* applied to the EUT at its various ports. However, in a compliance test a product manufacturer is interested in whether or not his product actually passes the test, that is, whether during the application of stress the product continues to function correctly against the performance criteria laid down for the test. In this context we are interested in the uncertainty of the *product performance*.

Therefore, given that we can quantify to some extent the variations in the level of the applied stress with external factors such as layout and impedances, the question arises as to how these variations translate into variations in performance of the EUT. To answer this it is necessary to know the *interference transfer function* of the EUT, which relates the applied stress level to the output variable which is being monitored to determine the EUT's performance.

If this interference transfer function is linear, then uncertainties in the applied stress will map directly onto uncertainties in compliance. But if it is non-linear, then this mapping is complicated: typically, small variations in applied stress will make large changes in response. And if the criterion is digital – for example, no change of state is allowed – and the output can take up either of two states, then if the stress uncertainty straddles the level at which change of state occurs, nothing can be said about the uncertainty of the output response. These situations are shown in Figure 23.

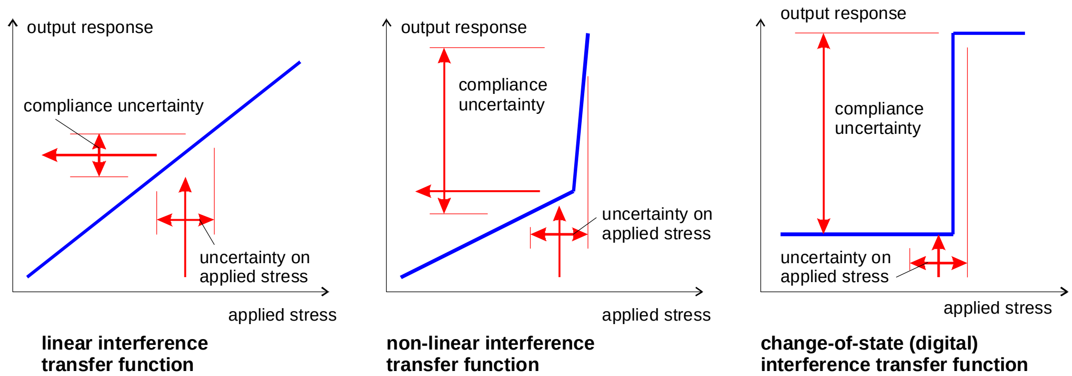

Figure 23 Interference transfer functions

In fact the interference transfer function is rarely known in advance for a given EUT, so that it is not generally feasible to make predictions about compliance uncertainty. If such predictions are demanded, then it is necessary to investigate the response of the EUT to changes in applied stress at all frequencies at which the information is wanted. Although such an investigation is perfectly feasible, for economic reasons it is not usually done by a manufacturer who only wants a compliance test.

This section of our report reviews work that has been done by various groups to investigate the susceptibility mechanisms of typical electronic circuits. From this we can deduce whether a particular class of circuit is more or less likely to have a linear interference transfer function, and hence see if there can be any helpful generalisations about the relationship between uncertainties in applied stress and uncertainties of compliance.

The review is divided into susceptibilities of digital circuits and of analogue circuits. From these reviews we then draw some conclusions about the susceptibilities of products containing either or both of these classes of circuit.

4.2 Digital circuits

4.2.1 Literature review

This section looks at a selection of the work that has been performed regarding the immunity of logic circuits, in chronological order.

RF Upset susceptibilities of CMOS and low-power Schottky D-Type Flip-Flops, Keneally, 1985 [22]:

Two D-type devices, a CD4013B and a 54ALS74A, are run through a sequence of functional tests to give a "normal operating baseline" with a clock frequency of 1.25MHz. RF is injected in turn onto the V_{CC} pin, the clock pin and the data pin at discrete frequencies from 1.2 to 200MHz and the power level needed to create an upset (deviation from the baseline) is noted. The paper gives frequency dependencies for upset levels for each device. The upset events were:

- for the CD4013B, the Q output stays high for 200ns too long before going low as intended;
- for the 54ALS74A V_{CC} input, not-Q went low one clock cycle before the intended high to low transition
- for the 54ALS74A clock and data input, Q and not-Q changed logic state one clock cycle before the intended transition.

RFI Susceptibility evaluation of VLSI logic circuits, Tront, 1991 [23]:

This paper examines the response of flip-flop storage elements to RFI-induced upset. It is only when an RFI-induced voltage or current changes the contents of a flip-flop that the system is actually upset. However, a path through a set of combinational logic gates is likely to have many more sites at which detrimental voltages will be generated than does a single flip-flop. Thus the paper discusses simulation of the effects of RFI impacting on combinational logic and propagating along a path to a flip-flop.

For an RFI pulse to cause an error, it must change the state of a flip-flop. So if a flip-flop is equally likely to be in either of two states, and if a positive going upset is equally as likely as a negative, then there is at most a 50% chance that an upset will occur as a result. Additionally, the operation of a flip-flop means that a pulse of interference must arrive at the flip-flop with sufficient amplitude when the clock is high, and must be sustained until the clock goes low (for flip-flops which latch on the negative going edge). The pulse must have been present for a minimum time equal to the sum of the flip-flop's setup and hold times.

From these considerations the paper derives the concept of an *upset window* (Figure 24), which is a graph for a particular circuit configuration showing the simulated levels which are needed to cause an upset when the interference arrives with a particular duration and at a particular time with respect to the clock transition.

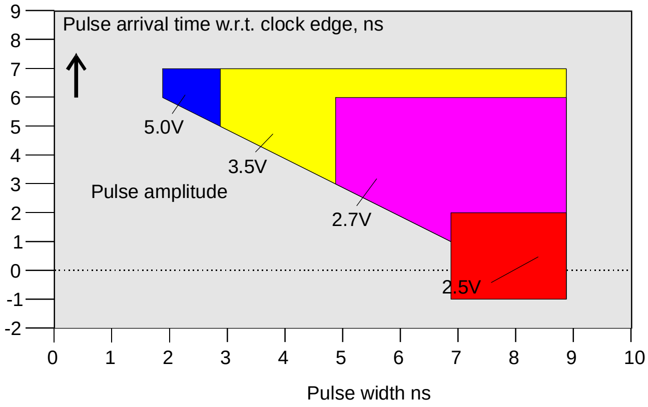

Figure 24 Upset window diagram for a chain of NAND gates feeding a flip-flop D input (after [23])

EMI-induced delay in digital circuits: Application, Chappel & Zaky, 1992 [24]:

EMI has been observed to have two distinct effects on digital devices. The first is false switching or *static failure*, which occurs when interference is of a sufficient magnitude to cause an otherwise static logic signal to appear to change state. The second effect is that of EMI-induced delays. Significant changes in the propagation delay of a device occur at much lower amplitudes than those that cause false switching, and are therefore the primary cause of failure in the presence of low level EMI. These changes lead to violations of critical timing constraints, such as the setup and hold times of flip-flops. They can be referred to as *dynamic failures*, and are dependent on the phase of the EMI with respect to the clock transition, unlike static failures. EMI-induced voltages that are lower than the circuit's noise margin will not change the state of a logic signal, but may still affect the operation of the circuit by changing its propagation delay.

The paper defines "delay margin", analogous to noise margin, as the maximum allowable change in the timing of a given signal transition for which the circuit will continue to operate reliably. A positive and a negative delay margin are associated with every transition. In a *synchronous* circuit, the main timing constraint arises from the need to ensure that the minimum setup and hold times of all storage elements are met; these define a window around the clock edge during which input data must be stable to guarantee correct operation. In an *asynchronous* circuit, data must maintain a correct timing relationship with control signals; if an initiation signal indicates that data is present and ready to be operated on, that data must actually be present. Or, if a completion signal indicates that a result is available at the output, that result data must actually be present.

The paper demonstrates this concept through both modelling and measurement on an example circuit.

Modelling of field-exposed digital circuits for the prediction of EMI immunity, Laurin et al, 1993 [25]:

The majority of the paper describes a modelling strategy with SPICE to determine RFI induced voltages. Change in propagation delay is said to be the primary cause of failure induced by low-level EMI. Linear analysis is sufficient to predict steady state voltages for induced RFI up to 1.5V peak-to-peak, for CMOS operated from a 5V power supply.

An illustration shows that RFI causes a spread of propagation delays, or skew, between two lines that have induced interference; these can be for instance a clock line and its associated data line. The actual skew depends on the relative phases of the RFI and the wanted signal edges. In the illustration, a 1m length of multi-conductor ribbon cable with CD4007A CMOS inverters at either end is exposed to a 10V/m incident plane wave at 1-4MHz and the modelled skew is shown to be as high as 60ns.

Susceptibility of CMOS and HCMOS integrated circuits to transient disturbing signals, Heddebaut et al, 1993 [26]:

Interference coupling to a line between a pair of gates is analysed and it is shown that the susceptibility is most critical during changes of logic state. The delay caused by interference is seen to be most affected by the dynamic output impedance of the driving gate, so that CMOS (4000 series) gives a high delay; HC devices a medium value, and AC substantially less. The curve of delay versus injected current is not linear.

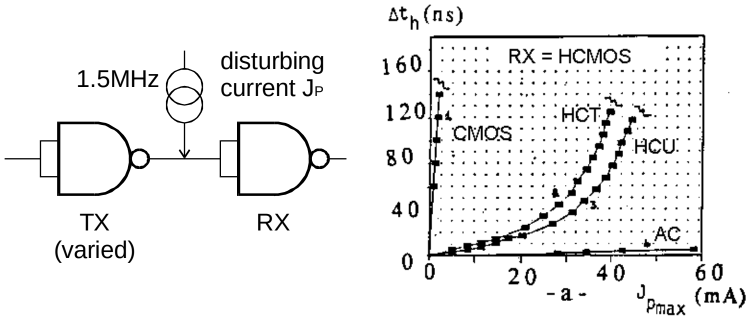

Figure 25   Measured delay for a pair of NAND gates with various driver technologies [26]

The paper also shows that dynamic output resistance can vary over a nearly three-to-one range for the same part from different manufacturers, which has potentially serious consequences for the variations in product immunity for products made with multi-sourced components.

Electromagnetic susceptibility of digital LSI circuits mounted on a printed circuit board, Klingler et al, 1993 [27]:

A pair of NAND gates of different technologies are exposed to a field from 1 to 200MHz in a TEM cell. The signal line between the gates is deliberately routed to induce interference in a specific plane with respect to the applied field. The gates transmit a pseudo-random binary sequence at 12.5Mbps, coupled through the cell via fibre optic interfaces, and the input signal is compared to the output in real time to detect errors. No storage circuits are used and so the method detects gross (static) failures rather than time delay errors (dynamic failures). Some of the conclusions are:

- TTL technologies (74LS, 74S, 74F) have a higher susceptibility level than CMOS (74HC) by a factor of two to three;
- significant differences (up to a factor of 5 times) are observed between the same type from two different manufacturers, although there is little difference between different parts of the same type from the same manufacturer;
- the figures (below) show a 74LS device with an interference frequency of 100MHz and levels of 51V/m and 66V/m; there is a rapid increase in data corruption between the two levels, and the technology is very sensitive to interference during low level logic states, regardless of frequency;
- HCMOS behaves differently, having similar behaviour for each logic state, but high and low susceptibilities are emphasised at different frequencies;
- deduced from the effect of orientation on susceptibility, the dysfunctions are the result of both electric and magnetic coupling. Observed anisotropy in the coupling is a result of the constructive or destructive contributions of the induced currents due to electric and magnetic coupling depending on orientation.

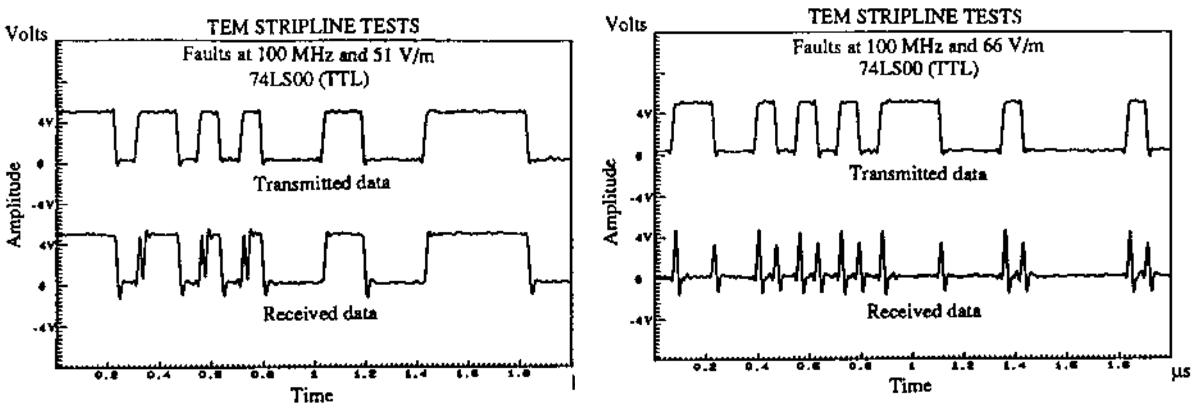

Figure 26 Effect of interference on 74LS00 NAND gates at two different levels [27]

Upset behaviour of LSI digital components submitted to electromagnetic disturbances, Klingler et al, 1995 [28]:

The relationship between electrical disturbance and behaviour is very difficult to identify and predict. Firstly, the interfering current and voltage levels depend on the impedance between pins of the components which are non-linear and not well defined at high frequencies. Secondly, the behaviour of a digital component will depend on its functional characteristics such as threshold levels, maximum frequency, timing limits etc. Once the electric levels are translated into binary levels, the outputs will finally be the result of a combination, sequential or memory function.

This means that to follow the process from interference to the binary result, different analysis methods must be adopted successively. First the EM energy must be translated into voltage and current sources applied to the components, taking into account the pin non-linearities. Then these levels must be translated to digital levels, and these must then be processed to obtain the dysfunction observed at the output of the digital circuit.

For in-band RFI (less than the gate's maximum working frequency), both CMOS and TTL technologies are sensitive around their threshold level and disturbances are transmitted to the output with significant levels. At higher frequencies, no spurious disturbances are propagated, but LSTTL gates suffer a shift in threshold voltage which will cause the output to saturate at a fixed level if the interference voltage is high enough. Statistical analysis of error levels with interference from 15 to 95MHz on a 2Mbps wanted data signal, shows that LSTTL circuits suffer systematic errors on the high output states only, while CMOS errors are very similar for both high and low states.

Effect of component choice on the immunity of digital circuits, Robinson et al, 1996 [29]:

Timing jitter induced by a series injected RF signal from 10 to 120MHz was compared for six different logic families, configured as 74XX04 inverters passing a 1MHz clock. The induced jitter was found to increase with RF voltage for all six families, and was generally different for rising and falling edges. There is a trend for the slower logic families to be more susceptible, although the most susceptible family was 74ALS rather than 4000B.

The increase in jitter time with applied voltage was not always, or even usually, linear. Since the switching waveform is not exactly trapezoidal, a non-uniform slew rate leads to a non-linear increase in jitter time with voltage at the higher levels. Also, the applied signal was modulated; this can be demodulated by non-linear elements within the IC, leading to additional disruption to the timing.

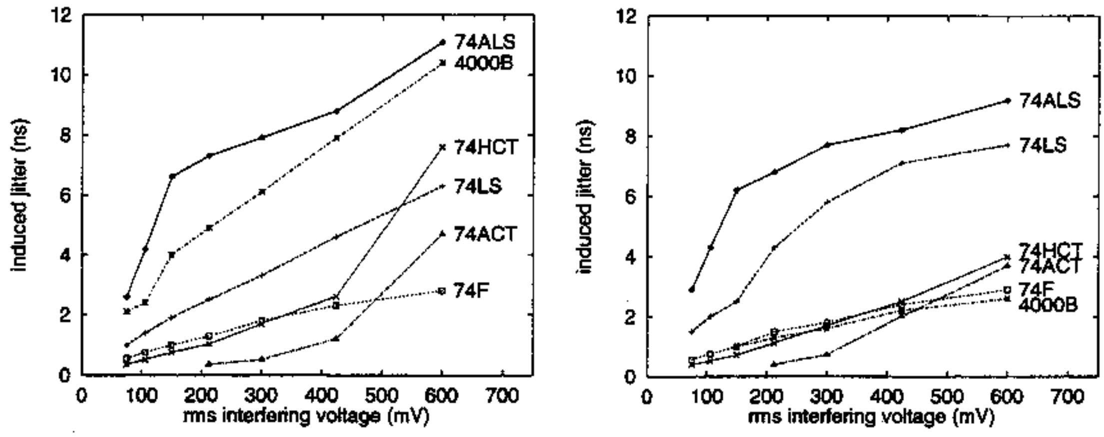

Figure 27 Variation of jitter with RF voltage at 30MHz (left) and 100MHz (right) [29]

4.2.2 Experimental work

The circuit described in Annex F was used to check the interference transfer functions versus frequency and level for a simple clocked digital logic circuit. The average output voltage of a clocked flip-flop was monitored; any deviation in this voltage implied a mis-clocking of the data. Usually in a real circuit this would result in a failure of the processing system.

As anticipated, absolutely no effect on the output voltage was observed up to some level dependent on frequency. Above this level a near-linear increasing deviation was observed, confirming that the effect is principally one of timing distortion, as proposed by the published work quoted above.

4.2.3 Conclusion

Digital *systems* are made up of a large number of individual digital *circuits*: typically, a microprocessor-based product will include multiple synchronous data lines transferring signals under clock control between the processor and its I/O and memory. Disruption to these transfers will not become apparent until either

1. the induced transition delays exceed the timing margins built into the synchronous circuitry (dynamic failure), or

2. the induced voltage exceeds the noise margin of the relevant interface (static failure).

Unless the circuit is designed to have substantial timing margins, (1) is likely to occur before (2) as the interfering stress is increased. Once a disruption to a data transfer occurs, it is not certain that a disruption to system operation will occur; this will depend on where in relation to the circuit, and when in relation to the operating cycle of the controlling software, the data transfer is affected. The disruption to the operation may be transient and invisible or recoverable, or permanent and un-recoverable. Thus the effect of a disruption can only be described stochastically. The process whereby the stress creates an effect is shown conceptually in Figure 28.

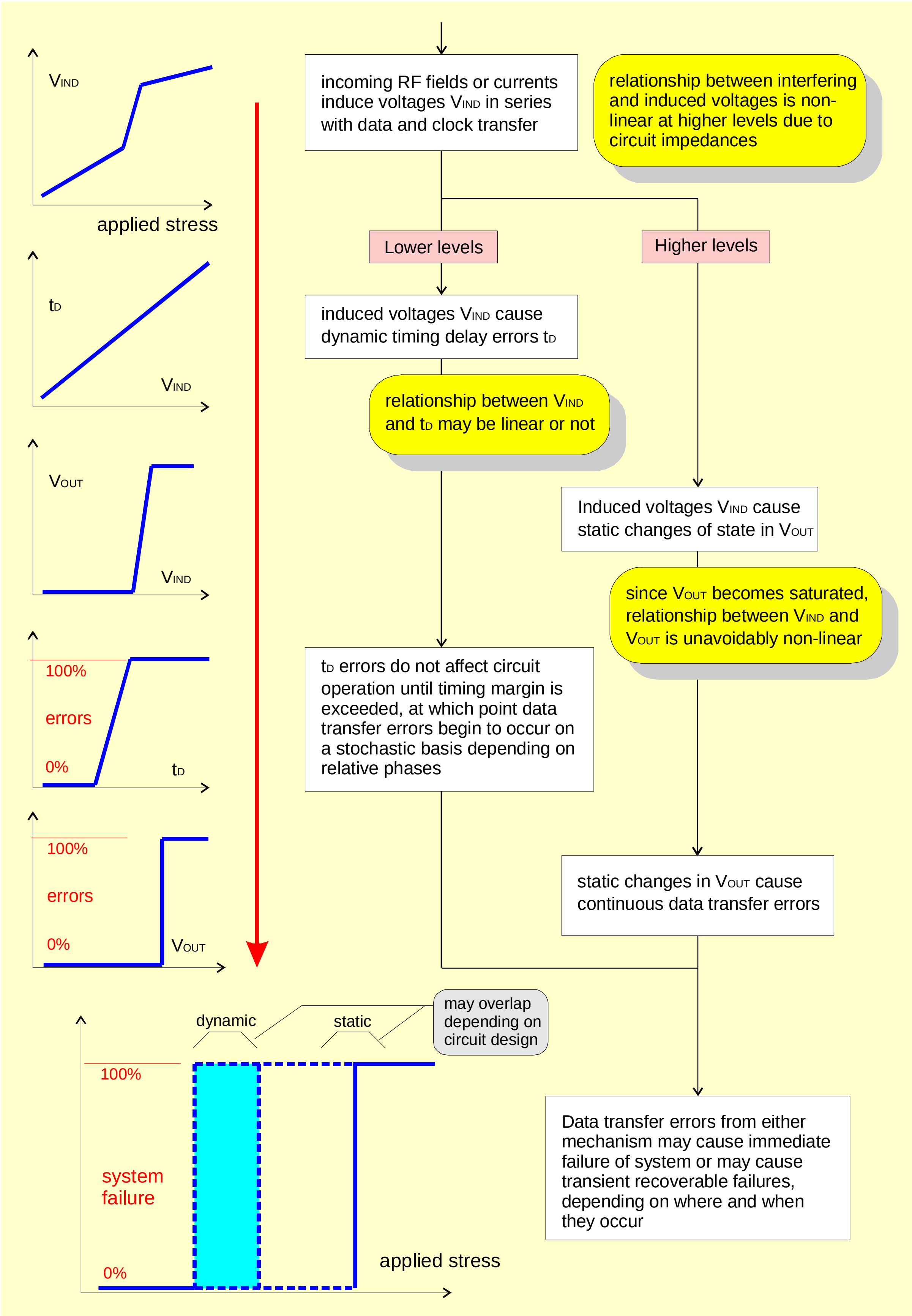

Figure 28 Conceptual process of interference in digital circuits

It can be concluded that the response of a digital system to interference is inherently non-linear and stochastic. No direct relationship between the uncertainty of the applied stress and the uncertainty of the compliance outcome can be established.

Some work on a novel method of determining RF immunity of digital circuits by observing their re-emission spectrum has been reported [30]. Before an actual functional immunity failure is observed, the non-linearities in the system cause intermodulation of the interfering signal and the operating clocks, which can be detected by performing an emissions scan simultaneously with a gradual increase of the interfering signal. Around the point of functional failure a discontinuity in the level of the intermodulation products is seen. While this technique gives an interesting and potentially useful diagnostic tool, it is not seem likely to gain widespread use as an alternative to the conventional method and only serves to emphasize the inherently non-linear nature of the system response in the conventional method.

As a side comment, the fact that several groups have observed dramatic differences in immunity between different manufacturer’s parts of the same type, means that even the actual level of the susceptibility threshold can vary from product to product if multi-sourced parts are used.

4.3 Analogue circuits

4.3.1 Literature review

This section looks at the work that has been performed regarding the immunity of analogue circuits, in chronological order.

Many papers exist on the theoretical analysis and modelling of operational amplifiers in the presence of RF interference. Not all of these give information on the linearity of response and are relevant to this project. Those that have been reviewed and fall into this category include [32], [34] and [38].

***Demodulation RFI in inverting and non-inverting operational amplifier circuits*, Sutu & Whalen, 1985 [31]**

Describes a measurement programme in which the statistics of the demodulation transfer function for a number of different operational amplifiers is determined. The frequency range investigated was from 0.1 to 400MHz and the transfer function is shown to be a square law.

***Simulation of the RF immunity property of analog circuits*, Worm, 1995 [33]**

Describes a simulation program in use at Philips which calculates the DC shift and low frequency demodulation which occurs due to the non-linear characteristics of the devices used. The effects are stated to vary with the square of the RF voltage applied.

***Comparison of the RF immunity of operational amplifiers*, Rahbek, 1997 [35]**

For RF voltages less than 0.2V RMS, the properties of an op-amp can be described by a frequency dependent Taylor expansion where the coefficient of the second order term is the dominant parameter. This results in DC offset or LF demodulation disturbances. Third order terms may also produce cross-modulation, where the modulated RF signal cross-modulates other LF disturbances to produce a noise signal on the frequency of the wanted signal.

Measurements on various devices show that detection is quadratic up to about 0dBm where higher order effects begin to occur. An example response is shown in Figure 29.

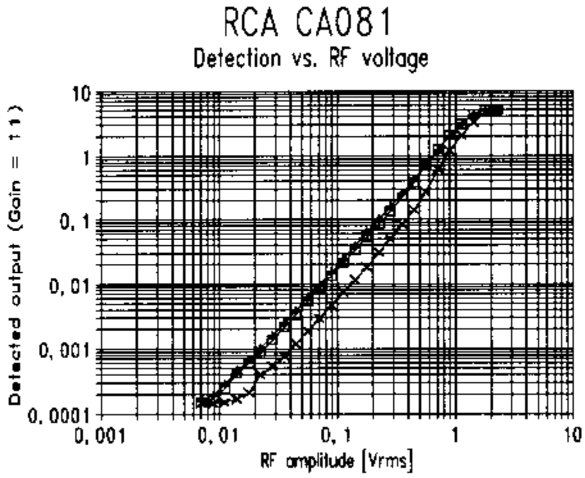

Figure 29 Demodulated output AF voltage versus RF amplitude [35]

Measurements on parts with the same part number but from different manufacturers show large differences in the detection coefficient between them.

***On the effects of RF interference in voltage regulator integrated circuits*, Fiori & Pozzolo, 1997 [36]**

Voltage regulators may be susceptible to injected RF voltage. Simulation shows a non-linear reduction in output voltage with increasing RF, which is confirmed by measurement (see Figure 30). The type of regulator device used for these experiments is not quoted.

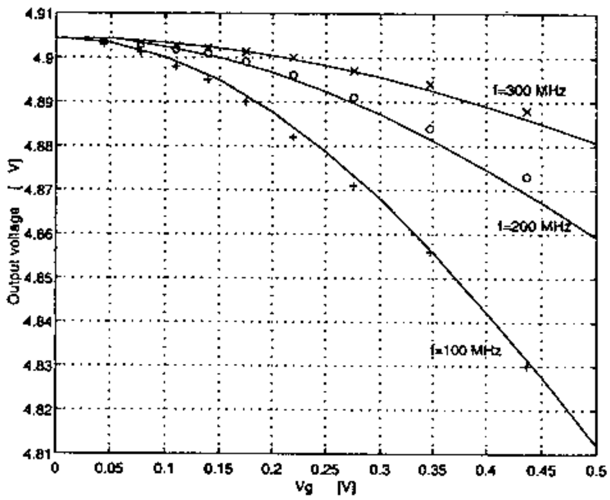

Figure 30 Voltage regulator output voltage versus RF voltage, simulation and measurement [36]

***Susceptibility of a bandgap circuit to conducted RF interference*, Fiori et al, 2000 [37]**

The bandgap integrated circuit is frequently used as a voltage reference in regulator and ADC modules of a circuit. Simulations show a non-linear reduction in output voltage, similar to that given in paper [36] above.

***Modelling RF interference effects in integrated circuits*, Whyman & Dawson, 2001 [39]**

The two papers referenced here describe the same work, which shows how the RF susceptibility process may be decomposed into two stages, using a two-layer model. The first stage consists of a linear model to represent the interference propagation to the pins of devices. This uses linear s-parameter measurements for each IC pin to be considered. The second stage of the model consists of a non-linear frequency dependent function to generate offset voltages that are injected into the low frequency circuit model, which can then be used to predict the system performance. Simple polynomial functions have been devised, from measurements, to give the correct device response to frequency and power of the injected RF.

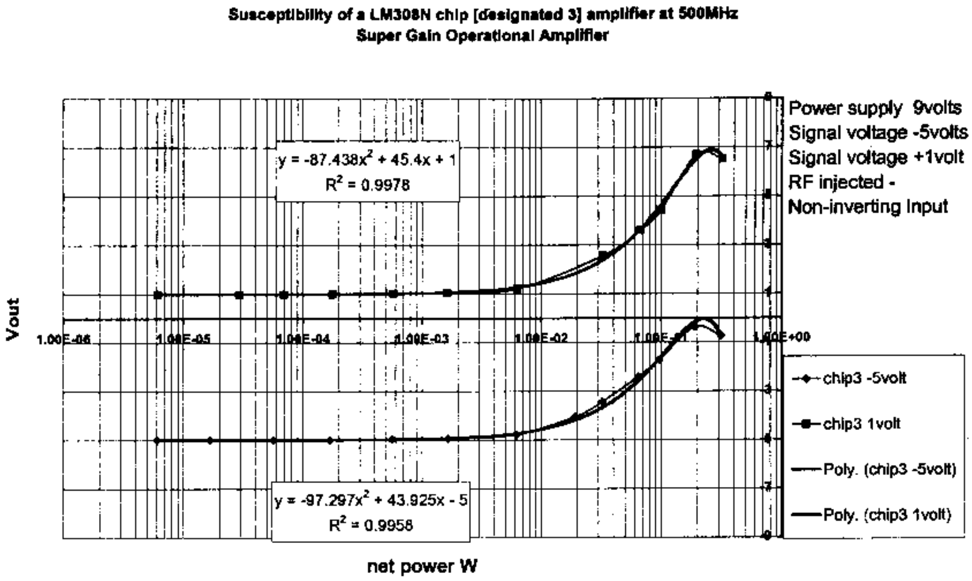

Figure 31 Measure offset voltages and polynomial approximation versus input power at 500MHz [39]

Analysis of EMI effects in op-amp ICs: Measurement techniques and numerical prediction, **Florean, 2001 [40]**

RF voltages are injected on input and supply pins of various types of operational amplifier. Some results of the variation with frequency and input voltage are reported. Examples are shown below.

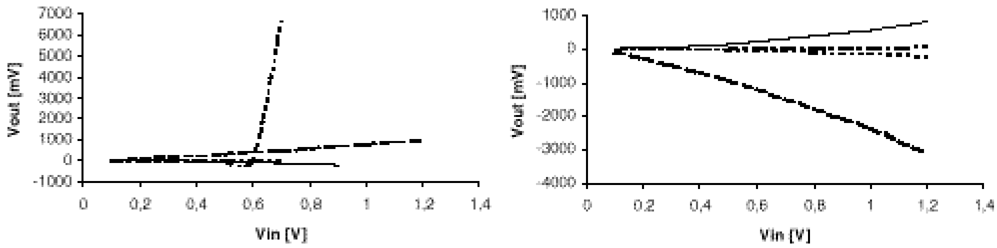

Figure 32 Voltage follower, injection into –ve supply pin (left); inverting amplifier, injection into –ve input (right) [40]

4.3.2 Experimental work

The circuit described in Annex F was used to check the interference transfer functions versus frequency and level for a number of common op-amp devices. Most of the published work concentrates on modelling the transfer function versus frequency, which does not illuminate the non-linear nature of the amplitude response at any particular frequency, so our work instead looks explicitly at the amplitude transfer at spot frequencies. The annex gives details of the results which can be summarized as follows:

- different op-amp technologies have different characteristic functions;
- for a given type, different responses can be observed at different frequencies;

- the DC operating conditions often have a marked effect on the response, and this is particularly noticeable when single-supply devices are operated close to their lower common mode voltage limit – a condition for which they are well suited and indeed specified in application terms;

- only one of the devices tested – interestingly, the oldest type, with an internal design dating back to the 1970s – showed a response that was approaching linearity over the range tested.

4.3.3 Conclusion

Analogue *systems* are made up of a large number of individual analogue *circuits*. Not all of these circuits will be critical to the performance of the system. Disruption to the output of any given circuit may take any of the following forms:

- no effect;

- an effect on the output variable that is linear with applied RF;

- an effect on the output variable that is non-linear, either quadratic (square law) or showing variations of a saturation characteristic with applied RF;

- an effect on the output variable that is bistable, that is, a quasi-digital effect, especially if there is frequency pulling between the applied interference and the operating frequency.

These circuit output effects are then propagated within the system and the same hierarchy of possible effects is repeated at the system level. Thus, while a linear or near-linear interference transfer function is possible, it is only one of a number of likely outcomes.

Therefore, as with digital systems, the connection between uncertainty of applied stress and uncertainty of response cannot be stated in general. Only if the most sensitive point at which interference affects the circuit is known, and then the interference transfer function of that point is also known, can a statement about uncertainty of response be made. Such knowledge is rarely if ever available to a test laboratory and even the circuit designer is unlikely to have access to it.

Overall, this conclusion means that it is not generally feasible to make a statement of uncertainty about the result of a radio frequency immunity test. Only the uncertainty of the applied stress can be quoted.

5 References

5.1 Conducted immunity testing

5.1.1 Standards

IEC 61000-4-6 Electromagnetic compatibility Part 4 – Testing and measurement techniques – Section 6: Immunity to conducted disturbances, induced by radio frequency fields

Outstanding documents:

77B/310/CD: Edition 2 of IEC 61000-4-6. Circulated for voting 5th January 2001. Synopsis of changes:

- explicitly allows either amplifier output or sig gen output to be used for level setting
- allows CDNs to be used as decoupling networks with RF port unconnected
- Fig 1 – direct injection now relegated to alternative for screened cables, clamp injection preferred
- 7.1.2 revised to make it less explicit
- new 7.2, procedure for CDNs – all CDNs to be loaded with 50 ohms
- revision and clarification of procedure in 7.3 (former 7.2) for clamp injection
- new 7.7, procedure for cables not exiting the bottom of the EUT, requires separate ground plane
- various clarifications and extensions in clauses 8 (Test procedure), 9 (Evaluation) and 10 (Test report)
- new fig 11, test setup for cables not exiting bottom of EUT

77B/345/CDV: Edition 2 of IEC 61000-4-6, successor to 77B/310/CD. Circulated for voting 1st March 2002. Synopsis of changes:

- further revisions to clause 7, now requiring only one 150Ω terminating network on untested ports, so that the CM impedance presented during testing remains at 150Ω. Clause 7 now has extensive revisions from the original.

ENV 50141, Electromagnetic compatibility – Basic immunity standard – Conducted disturbances, induced by radio frequency fields – Immunity test

The forerunner to the EN edition of IEC 61000-4-6, now withdrawn. Although basically the same as IEC 61000-4-6, there are some significant differences in the technical detail.

5.1.2 Papers on conducted testing

[1] *EMC Workbench: testing methodology, module level testing and standardization*, M Coenen, Philips Journal of Research Vol 48 1994 pp 83-116

Describes conducted immunity testing of PCBs using methods related to those of IEC 61000-4-6

[2] *Conducted RF emission and RF immunity testing*, M Coenen, Zurich 11th International EMC Symposium, March 1995, paper 41H2 pp 225-230

Compares the repeatability of conducted versus radiated tests on a quasi-theoretical basis, considering the variations in common mode impedance of cables and EUT ports. Useful for a statement of the statistical distribution of impedances.

[3] *Comparison of common mode impedance measurements using 2 current probe technique versus V/I technique for CISPR 22 conducted measurements*, B Harlacher & R Stewart, IEEE EMC Symposium 2001, Montreal, paper D2-A1-04

Shows that the CISPR 2-probe method is worse than the V/I method. Relevant for its review of cable impedance effects at LF and up to 30MHz.

[4] *A high frequency model of current probes for injection purposes*, G Cerri et al, Zurich EMC Symposium February 2000, paper 71K8

Models current injection probes by means of S parameters. Model and measurements demonstrate that dramatic variations in induced voltage occur from 100MHz upwards with mismatched cables.

[5] *Fundamentals of the EMC current probes*, L Millanta, Zurich EMC Symposium February 1997 paper 111Q1, pp 585-590

Describes current probe constructions and gives equivalent circuit. Coupling parameters, insertion impedance and capacitive loading are all described and analysed clearly and effectively. A useful reference for the analytical section of this project.

[6] *Evaluation of current probes in EMC tests*, B Audone & C Tredici, EMC 96 Roma pp 38-43

Describes areas of concern for repeatability, specifically the contribution of L_P which is a function of the cable under test and its position in the probe window, and the contribution due to varying load impedance. Also gives an abbreviated characterization of the probe parameters.

[7] *Aspects of the Bulk Current immunity test*, R F Burbidge et al, IEE 7th Int Conf on EMC, York, August 1990, pp 162-168

Effects of probe position are modelled using MININEC and experimentally determined. Useful for its description of using NEC/MININEC to model BCI tests

[8] *The EM-Clamp as economically feasible tool for susceptibility analysi*s, N Monteyne & J Catrysse, EMC Europe 2000 Brugge, Vol 1 pp 457-462

Describes basic properties and extended measurements to 1GHz with the EM clamp and compares it favourably with the BCI probe, showing that the latter can give up to 50dB variations in injected level, which the EM clamp does not. Directly relevant to this study, also references an MSc thesis as follows.

[9] *The product standard EN ISO 14982 for agricultural machinery and Bulk Current Injection as test tool*, N Monteyne, Project report for MSc degree, University of York, March 1999

Extends the above briefer paper, discussing aspects of the differences between the EM Clamp and the BCI probe, including the impact of the AE impedance, wire diameter, position of the transducer along the wire, and the distance from the wire to the ground plane. Several of the results of the thesis can be used to validate the conclusions of the current project.

[10] *Comparison between 4 current injection devices in the frequency range 0.15 – 230MHz*, CISPR/A/WG1, CISPR/G/WG3 (Berlin/Bersier,Ryser), October 1991

[11] CISPR/A/WG1 (Warsaw/Bersier, Ryser)1, *summarizing extract of documents on influence of the length and layout of the cable under test, and influence of the common mode impedance at the EUT side and at the AE side of the cable under test,* September 1992

[12] *Considerations on the use of a current clamp 5/1 as injection device*, SC65A/WG4 (CH-Bersier, Szentkuti)3, CISPR/A/WG1 (Bersier, Ryser)1, CISPR/G/WG3 (Bersier, Ryser)7, July 1992

[13] *Considerations on the use of a EM-clamp with additional ferrite tube as injection device*, SC65A/WG4 (CH-Bersier, Szentkuti)4, CISPR/A/WG1 (Bersier, Ryser)2, CISPR/G/WG3 (Bersier, Ryser)8, August 1992

The above four papers and others form submissions to the CISPR and IEC committees responsible for considering the specification of the test methods for the then-draft conducted immunity test standard. They explicitly compare the results of the EM-Clamp and current clamp methods and discuss the factors which affect these results. The data contained in these papers can be used to validate the conclusions of the current project.

[14] *Description d'une pince d'injection de courant HF, à couplage inductif et capacitif (pince EM), permettant d'induire des courants élevés dans la gamme 0.15 – 200 MHz*, R Bersier, Swiss PTT Report No. VD 24.204C, 9th July 1986

[15] *Description d'une pince d'injection de courant HF, à couplage inductif et capacitif (pince EM) utilisable de 0.15 à 200 MHz*, R Bersier, Swiss PTT Report No. VD 24.227U, 31st March 1987; contribution to 4th International French-language colloquium on EMC, Limoges, 23rd-25th June 1987

First reports describing the construction and use of the EM-clamp

[16] *Commercial and Military Current Injection Clamp Calibration*, Schaffner EMC Systems technical note, PUB 603

Explains why the requirements of IEC 61000-4-6 and DEF STAN 59-41 for current clamp performance are mutually exclusive

5.2 Radiated immunity testing

5.2.1 Standards

IEC 61000-4-3 Electromagnetic compatibility Part 4 – Testing and measurement techniques – Section 3: Radiated, radio frequency electromagnetic field immunity test

The second edition of this standard was published in 2002. Synopsis of changes from edition 1:1995 + its A1:1998:

- Scope, clause 1, now explicitly states that testing is not required at other frequencies than given in Clause 5
- Clause 6.2, Calibration of field, changed again to clarify the procedure for partial illumination of areas greater than 1.5 x 1.5m. Does not change other more controversial aspects of 6.2.
- Informative annex C on use of anechoic chambers expanded to include "suggested adjustments to adapt for use at frequencies above 1GHz ferrite-lined chambers designed for use at frequencies up to 1GHz". Proposes either using more directional antenna, or reducing the antenna-EUT distance to 1m, or adding carbon absorber to the rear wall.
- No change to Annex D on TEM cells and striplines
- New normative Annex J introducing "Alternative illumination method for frequencies above 1GHz (independent windows method)", which divides the uniform field calibration area into a series of 0.5 x 0.5m windows to cover the whole area occupied by the EUT, each window being calibrated (and tested) independently.

Outstanding documents:

77B/303/CDV: Revision of the calibration procedure and verification of the correct application of the modulation during the test. Circulated for voting 10th Nov 2000 (now approved for DIS). Synopsis of changes:

- revises clause 6.2, calibration of field: replaces procedure – points a) through h) in the original standard – with a more explicit procedure, with respect to discarding 4 out of 16 points, with a choice of either constant field strength or constant power. Insists that the calibration is carried out unmodulated at a field strength of at least 1.8 times the test field strength, to ensure the amplifier is not saturated by application of modulation.
- adds new Fig 7, measuring set-up block diagram, which is made mandatory

- removes anachronistic requirement of sweep rate of 1.5 x 10^{-3} decades per sec, replaced with minimum dwell time of 0.5 sec or enough to get a response from the EUT
- adds new informative Annex L discussing amplifier harmonics and giving examples of the new calibration procedures of 6.2

5.2.2 Papers on radiated testing

[17] *Specification of alternative test sites with respect to given EMC Field standards*, H Garbe et al, Zurich EMC Symposium February 1997 paper 87M6, pp 459-464

Proposes to replace the 75% rule for field uniformity calibration with a statistical procedure that requires the standard deviation of all 16 measurements to be ≤2.6dB, said to be equivalent to 75% coverage. Supports this with modelling of log periodic and biconical field distributions, does not account for chamber reflections.

[18] *A comparison of RF field uniformity in a compact semi-anechoic room and OATS*, J Teune & S Mee, IEEE EMC Symposium 2001, Montreal, paper D2-P2-02

Describes how beamwidth radiation pattern performance of double ridge waveguide and horn antennas from 200MHz to 4GHz, along with chamber wall reflections, affects field uniformity. Light on actual data.

[19] *The effect of measurement environment on the EMI performance of a generic EUT*, B Cahill et al, EMC 96 Roma pp 18-22

Investigates the effect of wave coupling with an EUT 0.6 x 0.5 x 0.3m in various test environments, particularly free space, conducting ground, strip line and TEM cell. Simulation and measurement only carried out over 100-150MHz and of most relevance to TEM cells, but may be of interest for this project. Shows distortion of surface current at the edges of the EUT

[20] *Some measurements of field uniformity within commonly used environments for radiated susceptibility measurements*, L Dawson et al, IEE 8th Int Conf on EMC, Edinburgh, September 1992, pp 43-48

Directly relevant to this project, it compares field uniformities in different environments (screened, anechoic, OATS and stripline) used for radiated immunity tests and proposes a measure of their acceptability, quoted as “Normalised Standard Deviation” of the field. Also describes the use of a dummy EUT to investigate the effect of the EUT on the uniform field volume.

[21] *Corrections to antenna factors for resonant dipole antennas used over a ground plane*, Alexander, M.J., and Salter. M.J, NPL DES Report DES 131-Draft, NPL, 1993.

5.3 EUT responses

5.3.1 Papers on digital susceptibility

[22] *RF Upset susceptibilities of CMOS and low-power Schottky D-Type Flip-Flops*, D J Keneally et al, IEEE EMC Symposium 1989, Denver, pp 190-195

[23] *RFI Susceptibility evaluation of VLSI logic circuits*, J G Tront, Zurich 9th International EMC Symposium, March 1991, paper 81L5 pp 425-429

[24] *EMI-induced delay in digital circuits: Application*, J F Chappel and S G Zaky, IEEE EMC Symposium 1992, Anaheim, pp 449-454

[25] *Modelling of field-exposed digital circuits for the prediction of EMI immunity*, J J Laurin et al, Zurich 10th International EMC Symposium, March 1993, paper 7B2 pp 29-34

[26] *Susceptibility of CMOS and HCMOS integrated circuits to transient disturbing signals*, B Heddebaut et al, Zurich 10th International EMC Symposium, March 1993, paper 10B5 pp 45-48

[27] *Electromagnetic susceptibility of digital LSI circuits mounted on a printed circuit board*, M Klingler et al, Zurich 10th International EMC Symposium, March 1993, paper 121R1 pp 651-656

[28] *Upset behaviour of LSI digital components submitted to electromagnetic disturbances*, M Klingler et al, Zurich 11th International EMC Symposium, March 1995, paper 47H8 pp 259-264

[29] *Effect of component choice on the immunity of digital circuits*, M P Robinson et al, EMC 96 Roma pp 233-236

[30] *Assessing the immunity of digital equipment using the emission spectrum,* I D Flintoft et al, EMC Europe 2000 Brugge, 4th European Symposium on Electromagnetic Compatibility, Sept 11-15, Brugge, 2000, pp 35-40

5.3.2 Papers on analogue susceptibility

[31] *Demodulation RFI in inverting and non-inverting operational amplifier circuits*, Y H Sutu and J J Whalen, Zurich 6th International EMC Symposium, March 1985, paper 64K3 pp 351-358

[32] *Undergraduate student projects on determining demodulation RFI statistics for operational amplifiers*, H Ghadamabadi et al, IEE 7th Int Conf on EMC, York, August 1990, pp 253-260

[33] *Simulation of the RF immunity property of analog circuits*, S Worm, Zurich 11th International EMC Symposium, March 1995, paper 70L1 pp 375-380

[34] *On the effects of RF interference on bipolar integrated circuits*, F Fiori & V Pozzolo, EMC 96 Roma pp 502-505

[35] *Comparison of the RF immunity of operational amplifiers*, J Rahbek, Zurich 12th International EMC Symposium February 1997 paper 8B3, pp 43-46

[36] *On the effects of RF interference in voltage regulator integrated circuits*, F Fiori & V Pozzolo, Zurich 12th International EMC Symposium February 1997 paper 93N4, pp 489-492

[37] *Susceptibility of a bandgap circuit to conducted RF interference*, F Fiori et al, EMC Europe 2000 Brugge, Vol 2 pp 321-324

[38] *Prediction of RF interference in operational amplifiers by a new analytical model*, F Fiori et al, IEEE EMC Symposium 2001, Montreal, paper D4-P1-07

[39] *Modelling RF interference effects in integrated circuits*, N Whyman & J Dawson, IEEE EMC Symposium 2001, Montreal, paper D4-P2-05; and *Two level, in-band/out-of-band modelling RF interference effects in integrated circuits and electronic systems,* N Whyman & J Dawson, IEE 11th International Conference on EMC (IEE Pub. 464), York, July 1999 pp 135-139

[40] *Analysis of EMI effects in op-amp ICs: Measurement techniques and numerical prediction*, D Florean et al, IEEE EMC Symposium 2001, Montreal, paper D4-A5-08

[41] *A novel approach to system susceptibility testing*, B Audone & A Lamprati, EMC Europe 2000 Brugge, Vol 2 pp 83-88

Proposes an evaluation of EUT malfunctions on a statistical basis rather than qualitatively, shows how this may be done in practice with a simple series regulator circuit

5.4 General

[42] *Numerical electromagnetic code*, Logan, J.C., and Burke,A.J., Naval Oceans Systems Centre, CA, USA, 1981

[43] *The Expression of Uncertainty in EMC Testing*, UKAS publication LAB 34, Edition 1, 2002

[44] *EMC Measurement Uncertainty: A Handy Guide*, Schaffner EMC Systems, 2002