Antennas for EMC Applications

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EMC antennas are discussed in terms of applications, specific tests and testing problems. Also addressed are some widely-held misconceptions about antennas and the determination of far-field distance.

EMC Antennas

In discussing the individual EMC antennas, it is important to summarize what our definition of an antenna should be. For example, a prime consideration for a good antenna is that it be either resonant at the desired operating frequency or that it be a broadband design that is well matched and will cover a wider range of frequencies with good radiation efficiency. Since narrowband antennas are not practical for most EMC testing, this discussion will be limited to the broadband designs.

Some EMC Antenna Ground Rules

Impedance Match

The antenna should present a reasonable impedance match to the driving amplifier or to the receiver. A VSWR of 2:1 or better should be considered a desirable goal. An exception may be in EMC emissions applications where the antenna can be "padded" with a 50-ohm attenuator. In this case, allowance is made for the attenuator loss by combining it with the antenna factor. As long as the resulting receiver sensitivity is still adequate, the padding of an out-of-band antenna is acceptable. An example of an antenna being used out of band is the biconical antenna at 30 MHz and lower. Antenna padding, however, is not a practical accommodation for immunity testing. Attenuator pads will not only waste RF power, they will invariably do so in the very frequency bands where antenna efficiency is already very poor.

Antenna Efficiency

The antenna should provide reasonable power to field generating efficiency (gain) over the specified frequency range. If, for example, antenna gain decreases sharply at an extended lower frequency range, such as is the case with the biconical antenna at 25 MHz, the harmonics of the lowest test frequencies may be comparable to, or even exceed, the desired test frequency. This can occur because power amplifiers will generate high harmonic levels when they are over-driven, and power amplifiers are more likely to be over-driven when antenna efficiency is low.

Good EUT Coverage

Antenna pattern coverage should be reasonably uniform over the entire area occupied by the front face of the EUT. (This is an IEC 1000-4-3 requirement.) Not only will marginal coverage result in sharp field gradients across the EUT, marginal coverage may even make it impossible to meet the 0- to 6-dB field variation required for the IEC 1000-4-3 immunity test specification. Further, uniform EUT amplitude coverage is, in fact, *one* of the reasons for requiring that the testing be done in the far field.

A Low Frequency Test Limit

The test room should be large enough to accommodate the antenna and the wavelengths of the lowest test frequencies. The measure of this is that the width and height of the room should be at least ½ wavelength long. This is necessary in order to propagate the lowest waveguide mode along the length of the room in vertical and horizontal polarization with minimum loss. As frequency is increased above the first waveguide mode, and if the room is adequately anechoic, the room will soon support a free space radiated wave front.

Another consideration for the low frequency room limit is the fact that antenna gain and antenna factors are determined on open area test sites (OATS). Using these figures for measurements made in an undersized room will result in significantly higher path loss (lower effective gain) and erroneous test results.

EMC Antenna Types

Four common antenna types used for EMC applications are addressed. They are single-element antennas, multi-element antennas, horn antennas and antennas that employ parabolic reflectors. While not true antennas, the so-called E-field generators will also be touched on as well.

Single-Element Antennas

The most common single element antenna used in EMC is the biconical antenna (Figure 1). It is also the most misused antenna for EMC applications. Originally specified for military testing from 30 to 300 MHz at a distance of 1 meter, the biconical antenna and the bow-tie portion of a combination antenna (log periodic and biconical) are now used at up to 3 meters from the EUT and at frequencies down to 20 MHz.

*See advertisement on page 53

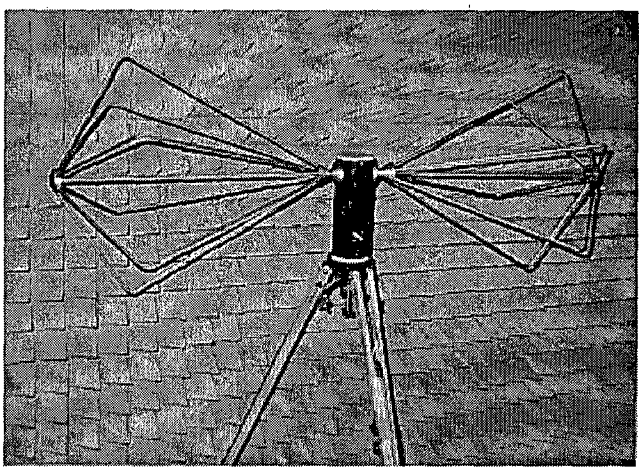


Figure 1. Biconical Antenna.

BACKGROUND ON MILITARY STANDARD TESTING AND THE BICONICAL ANTENNA

In an effort to achieve the broadest possible frequency coverage for military standard radiated susceptibility testing, the useable frequency range of the biconical antenna was redefined for EMC applications. Although the VSWR of the antenna rises to greater than 20:1 and the gain is 14 to 20 dB lower than at 80 MHz, the antenna was recommended for use down to 30 MHz. With military testing once performed in bare metal rooms, the chance for the enhancement of harmonic frequencies was high and directly proportional to the 'Q' (conductivity) of the room. While this harmonic enhancement was a potential problem at all test frequencies, the results are much worse when the fundamental frequency is below the room cut-off frequency and the harmonic frequencies are not.

The sensible solution for the low frequency limitations of antennas and test rooms is the use of conducted testing, whereby both emission and immunity testing are performed with monitoring probes and injection clamps. A good reference for the proper division of radiated immunity testing and conducted immunity testing is the IEC 1000-4-3 document. IEC 1000-4-3 directs that radiated immunity testing is to begin at 80 MHz and continue to 1 GHz. It further directs that conducted immunity testing (addressed in IEC 1000-4-6) is to begin at 80 MHz and continue down to 150 kHz. This minimizes the chances for harmonic problems in immunity testing and the uncertainty of reaching the desired exposure levels, at the desired frequency. Note that harmonics are not a problem in emission testing because the measurement instrument is a tuned or swept receiver. With antenna factors applied, the frequency response is essentially flat, and therefore, enables an accurate assessment of the radiated field components.

Biconical Antenna Facts

BALUNS

A balun (balanced-to-unbalanced) transformer is needed to provide equal drive to each dipole element half and to minimize feed cable radiation. The flaring of the antenna biconical antenna elements:

- Provides capacitive loading to reduce the length of the dipole elements.
- Determines the impedance of the antenna.
- Maintains a boresight major pattern lobe.

NOTE: Capacitive and/or inductive loading is employed to improve the impedance match and antenna gain at frequencies lower than the calculated length for a ½ wavelength dipole would ordinarily permit. However, regardless of the low frequency improvement made on the antenna, if the room is not large enough to accommodate the wavelength, antenna efficiency may be degraded to the point of being useless for the intended low frequency use.

MULTI-ELEMENT ANTENNAS

The most common multi-element antenna used for EMC testing is the Log Periodic (Figure 2). This antenna type is ideal for EMC testing because it exhibits near perfect performance over very wide bandwidths. With typical 10:1 frequency coverage or more, it provides virtually constant gain and beamwidth over the entire operating frequency range. Aside from cable and other transmission line losses, there is no theoretical limit to the frequency coverage for a log periodic design. However, practicality for EMC as well as other applications dictates both low and high frequency limits.

LOW FREQUENCY LIMITS

Low frequency operation is limited by the longest practical low frequency elements. For EMC applications, both the antenna and the wavelength must "fit" in the test room. The antenna should also have reasonable clearance, such as more than 1-meter distance from the antenna elements to each room surface. The distance to the EUT is, of course, 3 meters and the distance from the EUT to the wall, about 2 meters or as dictated by a field uniformity test.

HIGH FREQUENCY LIMITS

Limiting the high frequency coverage is the diminishing size of the dipole elements relative to the dimensions of the antenna boom and the feed cable. Both the impedance and the radiating efficiency of the antenna are strongly influenced when the dipole elements are dominated by the size of the feed end structure.

BOOM LENGTH

For EMC applications the overall length of the antenna should not exceed approximately 1/3 the transmit dis-

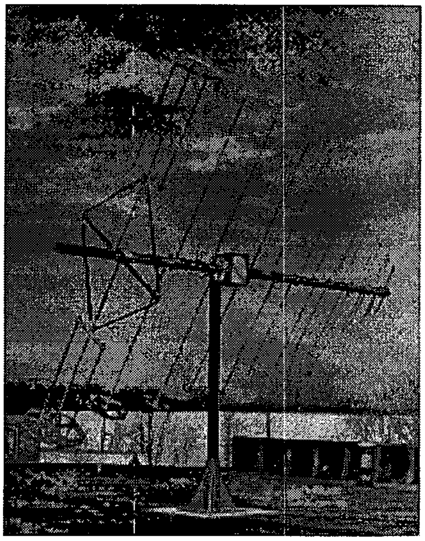


Figure 2. Log Periodic Antenna.

tance (Figure 3). However, this can be relaxed if there is adequate space in the test room and allowance is made for the increased transmitting distance between the low frequency antenna elements and the EUT.

For EMC applications, we may consider 80 MHz as the lowest practical frequency in compact anechoic rooms and 18 GHz as the highest in all test rooms and situations. This does not imply that a 80 MHz to 18 GHz log periodic antenna is a practical design. In fact, attempts at doing this result in a very large structure with significantly reduced power handling capability. As a rule, printed circuit log periodic designs are used above 1 or 2 GHz and solid rod elements with substantial solid booms are used at lower frequencies.

It is informative to recognize that at any given frequency in the band, only three major elements are involved in producing the effective radiated field. The one closest to resonance is the driven element, the adjacent, longer element acts as a reflector and the adjacent, shorter element acts as a director. Log periodic antennas can be designed with more antenna elements involved at each frequency for higher gain but the price for this gain improvement is increased antenna length and decreased bandwidth (Figure 4). Typical EMC log periodic antennas provide approximately 6 dB gain. Gains of approximately 8 dB or more can be achieved with a higher length to bandwidth ratio.

NOTE: The element lengths in a log periodic antenna are scaled in a constant ratio with frequency. However, not often recognized by the user is the fact that every other physical aspect of the antenna should also be scaled in the same ratio. This applies to element thickness and the boom thickness as well. However, for practical reasons such as cost and "good enough" results, most log periodic designs adhere to this principle in a step function rather than a precise, continuous taper.

Horn and Ridged Horn Antennas

Because of their higher gain and the need to generate high field levels for military standard testing, horn antennas have found wide acceptance for the application (Figures 5A and 5B). Double-ridged horns were and still are particularly popular because of the combination of relatively high gain and extraordinary broadband coverage. Standard gain horns, with their even higher gain but <2:1 frequency coverage are only used when the available RF power is low and higher gain is needed to reach required test levels. Bridging the gap between the very broadband, double-ridged guide horns and the sub-octave, standard gain horns are octave (≥2:1) band, ridged horns with small ridges. Octave band horns are most useful when matched with octave band TWT (traveling wave tube) amplifiers as they eliminate the need for high power switches. While a single double-ridged horn is ideal for emission applications from 1 to 18 GHz, it is less desirable yet still often used for immunity testing over the same range. However, because of the commonly used narrow band TWT amplifiers, high power switching must be used to enable a practical broadband test system.

While popular for military testing and other high field applications, horn and ridged horn antennas present problems for IEC 1000-4-3 testing. IEC testing requires that the minimum to maximum field variations at every test frequency not exceed 6 dB over a 1.5 meter square, vertical plane. This means that the combination of antenna pattern roll-off and the reflections within the imperfect anechoic room must not

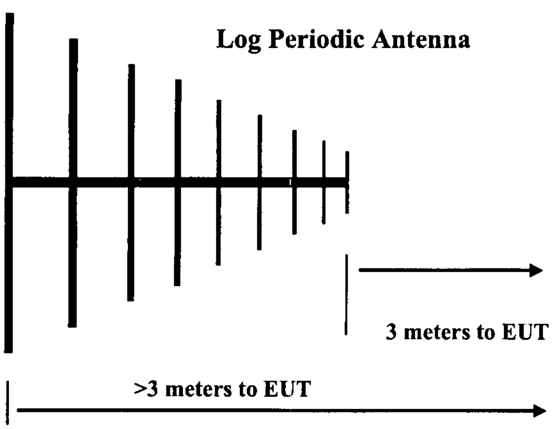


Figure 3. Effective Transmit Distance.

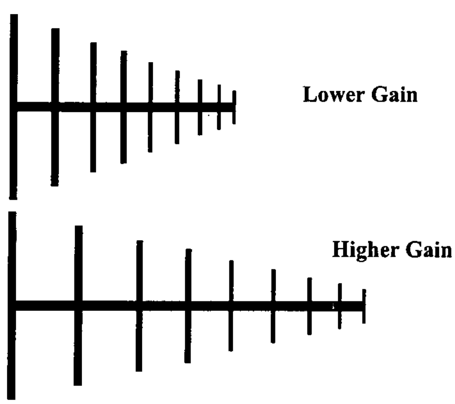


Figure 4. Log Periodic Antennas with Equal Bandwith.

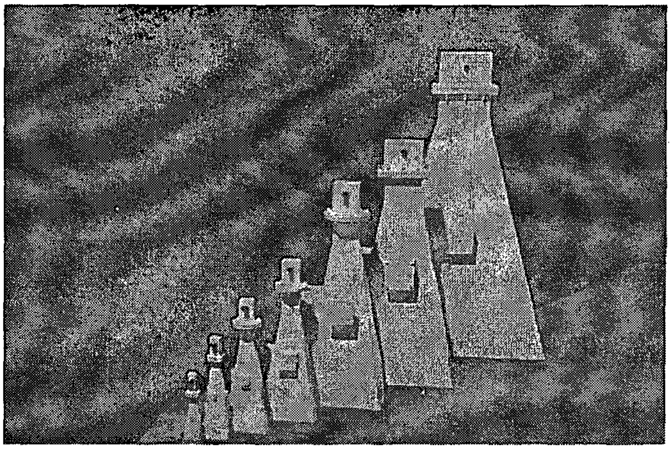


Figure 5A. *Standard Gain Horn Antennas.*

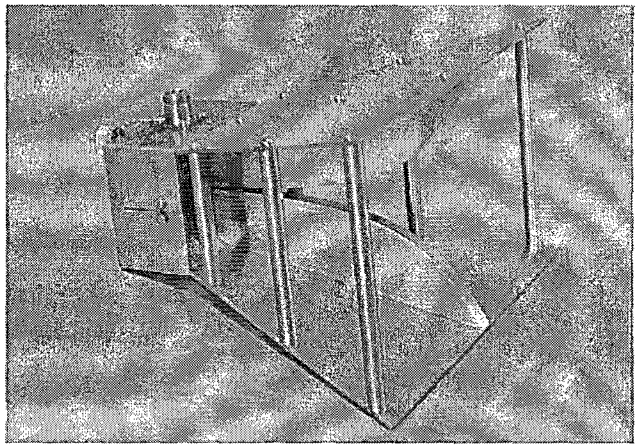


Figure 5B. *Double-ridged Waveguide.*

exceed 6 dB. Since horn antennas have relatively narrow beam widths, most of the allowable field gradient may be taken up by the horn pattern with little margin left for room reflections. In some cases, the horn antenna beamwidth may be so narrow that it alone would exceed the 6-dB requirement.

Horn Antenna Facts

- The opening of the flare, relative to the wavelength, determines the gain of the antenna (for standard gain and octave band horns).
- The flared horn aperture provides a smooth transition from waveguide transmission line to a radiating aperture with good impedance match.
- Ridged and double-ridged horns provide capacitive loading to make the horn feed and aperture appear electrically larger than the horn's physical size. This enables lower frequency operation for a given sized horn antenna.
- The radiation from ridged horns is more dependent on the ridges themselves than the apparent horn aperture. This can also be viewed as due to the heavy capacitive loading of the ridges and the resulting lower Q.

Parabolic Reflectors

Because of their extraordinarily high gain and narrow beam width, the use of this antenna in the confines of typical anechoic rooms is questionable at best (Figure 6). While generated field strength can be measured to some extent with field sensors, both the phase and amplitude of the radiated wave across the EUT is generally unknown. Further, because of the small radiation "spot" size, the EUT must be exposed in sections. More often than not, the partial EUT illuminations are calculated based on predicted far field performance. In truth, both the prediction and the direct field measurement are meaningless as a simulation or confirmation of conditions that may be encountered in space.

NOTE: In an effort to achieve mandated *HIRF (high intensity radiated fields) test levels with broadband amplifiers, the EMC engineer is often forced to use narrow beam parabolic reflectors spaced 1 meter from the EUT! This, even though it is recognized that the only practical way to perform this test is to place the EUT at the required distance from the actual threat emitter.

Broadband simulations of high power, narrow band emitters such as multi-megawatt radar are just not practical in anechoic rooms! Perhaps a better solution is to impose a minimum shielding effectiveness on aircraft so that onboard avionics will be subjected to significantly lower field levels. Currently, the imposed test levels for avionics are those that the aircraft skin may be subjected to. No allowance is made for even incidental aircraft shielding.

**A relatively new commercial aviation requirement for testing to "High Intensity Radiated Fields." These are fields that aircraft may experience when flying near radar and other high power transmitters.*

Far-Field Calculations

Although very sound methods for determining far-field distances are well defined in texts and reference guides, we too often misuse or misinterpret the general formulas.

Some of the commonly used formulas and estimates for determining the far field are: $\lambda/2$, λ/π, $\lambda/2\pi$, 10 wavelength and $2d^2/\lambda$.

If we think about microwave frequencies and higher gain antennas, we should realize that the first three expressions and the rough rule of thumb must only be true for very special cases at best. For example, we know that a 1-meter parabolic dish at 10 GHz would reach far-field conditions well outside of the bounds of the typical test room because of the very narrow beamwidth. However, using the first three equations and the rough "rule of thumb," we would calculate:

$\lambda/2 = .03/2 = .015$ meters
$\lambda/\pi = 0.03/\pi = 0.0096$ meters
$\lambda/2\pi = 0.03/2\pi = 0.0048$ meters, and
10 wavelengths = 10 x 0.03 = 0.3 meters

Using these guidelines, it appears that we can place an EUT less than

1 meter from the narrow beam antenna; however, common sense tells us that this cannot be true.

Using the more appropriate expression for large aperture antennas, we calculate:

$$2d^2/\lambda = 2(1^2)/0.03 = 66.7 \text{ meters.}$$

This is a much greater distance and one that intuitively makes sense for the described "pencil beam" antenna.

While the first three formulas are wrong for this example, there are conditions where they are reasonable approximations. We can, in fact, derive one of the equations starting with $2d^2/\lambda$.

Assume the longest dimension of the antenna is ½ wavelength (a dipole), then calculate the following:

$$2d^2/\lambda = 2\,(\lambda/2)^2/\lambda = \lambda/2$$

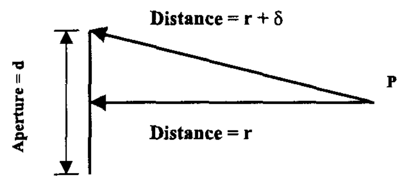
Lambda (λ) turns up in the numerator, and only the constants differ (2, π, and 2π). We should realize that the definition of far field is really an acceptance of some arbitrary but reasonable phase and amplitude difference across the antenna or EUT area. The formulas, $\lambda/2$, λ/π, and $\lambda/2\pi$ for $1/2\lambda$ antennas are OK for EMC purposes and for the purposes of an EMC standard, it is only a matter of settling on the definition that is "good enough."

Figure 6. Parabolic Reflector.

THE DERIVATION OF $2d^2/\lambda$

The following expressions, diagrams and equations are from "Antennas" by John D. Kraus (1950).

The field from a source travels a distance r to the center of a target and a distance r+δ to the edge of the target. Conversely and identical by reciprocity, we could consider the source as points on the antenna aperture to a target. In both cases, we are describing a phase difference across an antenna aperture or at a target due to the difference in transmission path lengths.



We can describe the relationships between aperture and distance traveled as follows:

$$(r + \delta)^2 = (1/2d)^2 + r^2 = r^2 + d^2/4$$

Assuming $\delta \ll d$ and $\delta \ll r$. Then $r \approx d^2/8\delta$

Using this expression and a commonly accepted tolerance for δ in terms of wavelength ($\lambda/16$), we arrive at:

$$r = d^2/8(\lambda/16) = 2d^2/\lambda$$

We can also see that selecting a tolerance other than $\lambda/16$ would result in some other constant. In general the constant may be represented by k so that $r = kd^2/\lambda$.

We may now determine a formula for $\lambda/2$ antennas based on the allowable phase difference across the aperture or target that can be tolerated for any given application. In so doing, we could, of course, also arrive at λ/π or $\lambda/2\pi$ as the suitable dipole near-field distance.

VERY SHORT "ANTENNAS"

We encounter equally strange problems when we try to apply the far-field equations to very long wavelengths and short antennas. Recall that we often test down to 20 MHz, where the antennas and even the room are too small. For military testing the problem is even worse with "radiated" testing starting at 10 kHz. In these cases, there is no point in trying to work out a far-field expression because the "antennas" we use are not antennas at all. Placing enough voltage on these devices produces an electric field that can be measured with a field sensor. However, the field around them is more akin to the field that exists around a parallel plate or wire transmission line, that is, a non-radiating TEM mode.

E-FIELD GENERATORS

The aforementioned low frequency antennas are commonly called E-field generators for want of a better name (Figure 7). They are not antennas even by our loose EMC definitions.Therefore, none of the formulas we use for calculating field strength, power and distance apply.

Starting with a voltage on a simple parallel plate line, we can calculate the field in volts/meter between the parallel plates by dividing the applied voltage by the separation of the plates in meters. We could also measure the field strength in the line with a simple E-field sensor and obtain near perfect agreement. Moving the field sensor from between the plates to distances outside the line, we will see that the field falls off very rapidly. We would then confirm that it is not possible to generate a field that will propagate over the EUT as a free space radiated field would.

The validity of testing down to very low frequencies is questionable and dependent on the intent. If the purpose of the test is to simulate very low frequency transmitters such as AM broadcast transmitters or lower frequency military transmitters, the "radiated" test in a shielded room is not representative of the RF threat condition. However, if the intent is to determine immunity or susceptibility to low frequency fields from video monitors, television sets or

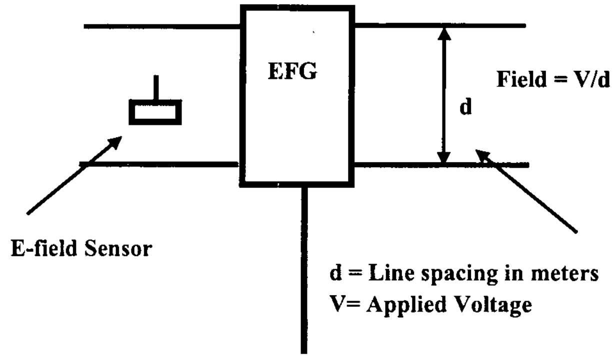


Figure *7. E-field Generator (EFG).*

other devices with low frequency, high voltage sources, the test may be valid. As concluded earlier, a much better way to test the immunity or susceptibility to relatively long wavelengths is to inject currents and voltages directly onto the EUT cables as described in the conducted immunity test procedures.

Summary

- Before selecting an antenna and a band of frequencies to cover, carefully consider the performance and limitations of the antenna, the test equipment and the anechoic room.
- It is recommended that radiated immunity testing for most test rooms and antennas start at 80 MHz. The IEC did an excellent job in making this determination.
- Conducted testing should be used in place of radiated testing below 80 MHz.
- For uniform illumination of the EUT as per IEC 1000-4-3, only biconical and log periodic antennas should be favored. Unless carefully selected and confirmed in the test room, horn antennas should not be assumed adequate for meeting the uniform field requirements of the standard.

TIM D'ARCANGELIS *has broad experience in RF and microwave systems, including 27 years in developing and leading the development of high-power broadband amplifiers, E-field sensors, antennas, TEM cells, multi-channel controllers and software. Many of these products were EMC industry firsts. Tim held positions of product engineer, product engineering manager, director of RF technical sales, vice president and president during a 27-year career at Thermo Voltek, Scientific Power Systems and Instruments For Industry. He is presently the EMC Manager at Antenna Research Associates, Inc., and can be reached at (516) 563-3616.*