Generating high field intensity for vehicles immunity tests in the HF-VHF range

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Abstract – The problem is that of generation of high E-field intensity in a large volume of space to illuminate a vehicle for RF field immunity tests, overcoming the common difficulties related to scarce gain and poor Voltage Standing Wave Ratio at antenna input in the High Frequency-Very High Frequency range. A set of requirements is derived and then a first examination of candidate antenna architectures is presented, while attention is focused then on symmetric spiral antennas.

I. Introduction

The need of high E-field intensity in a relatively large portion of space arises from a series of Standards and EU Directives regarding the radiofrequency (RF) immunity testing of vehicles and similar apparatus [1][2] and of military equipment.
It is underlined that high gain antennas may not be suitable for the frequency range of interest (between 20 MHz and up to approximately 100 MHz) and to ensure a given E-field uniformity over a rather large volume of space, in the order of several cubic meters. However fixed installations like those suggested for immunity testing of military vehicles and large equipment may take one whole day for mounting and dismounting and may interfere with the aerial current conductors for trolley systems (e.g. trolley buses).
Electric field intensity must be as high as 30 V/m at about 1.5-2.0 m from antenna center, depending on the size, shape and orientation of the antenna and on the transverse dimension of the region of space where the field level is specified. For high directivity antennas the distance must be increased for the main lobe to „cover" the same region of space at the expense of a larger amplifier rated power.
Antennas used for this task are all of biconical type, with adequate beamwidth, but very poor Voltage Standing Wave Ratio (WSVR) as high as 6:1 and a moderate gain, approximately that of a dipole; this imposes a costly requirement on minimum feeding amplifier power, that usually is in the range of some hundreds watts; amplifiers of this size are not only expensive but difficult to find. Moreover, a circularly polarized antenna avoids the change of orientation required by biconical and similar antennas, reducing to one half test duration. Another pitfall of biconical antennas is that the input impedance and the radiation pattern are strongly dependent on capacitive coupling to ground, different for vertical and horizontal orientations; also meaningful common mode coupling may occur with the feeding cable, thus reducing emitted electric field.
Main requirements for the foregoing analysis are:

- the frequency interval [f_{min}, f_{max}] preliminarily set to 20-100 MHz, with possible extension up to 120-150 MHz;
- size limited to a diameter of 1.5-1.8 m, in order to carry and handle single components;
- assembly and mounting operations as fast as possible;
- minimum beamwidth of approximately 60° that at 2 m distance illuminates uniformly a 2 m width object;
- VSWR at antenna connector limited to 3:1, possibly 2:1.

At least two differences characterize the proposed antenna with respect to commonly referred spiral antennas. From Milligan [3] we read that "spiral antennas consist of a thin metal foil spiral pattern etched on a substrate and located over a cavity": this is usually done for small microwave spiral antennas build on a dielectric substrate, while in our application the focus is on HF-VHF frequency range, so that the size is much larger, for robustness and convenience the foil is replaced by a wire or a strip (and self-complementary property is compromised) and there is no room for an efficient cavity at such a low frequency, so that it will be proposed to replace the cavity with a reflective ground plane.

II. Spiral antenna design concepts

In the following, if not explicitly said, the archimedean (that is not strictly a frequency-independent antenna structure because the spacing between arms is specified by a constant, not an angle) and the log spiral will be considered alike, so to exploit the results on the latter that are more abundant and easy to obtain. The main references for spiral design and behavior date back to late 50s [5][7] with attention concentrated on the log spiral. The main relationships for an archimedean spiral follow:

- the trajectory of one arm is defined by $r=a\phi$, where a is the expansion coefficient and ϕ is the rotation angle on the plane where arms lie; the other arm, for a two arms spiral, is obtained with a rotation of 180°;
- the two extreme points of the arm strip centered on (r,ϕ) are given by $r_{1,2}=a(\phi\pm\delta/2)$, where δ is the angle the gives strip radial width $w_r=a\delta$, that is independent on radius r itself; in our case, where a thin wire or a small strip is used, the value of δ approaches zero; the actual width is more precisely $w=w_r\sin\psi$, where ψ is the pitch angle (complementary of the increase angle of the arm);
- analogously, the radial spacing between the centerlines of adjacent turns of the same arm is $s_r=2\pi a$, but the actual spacing is $s = s_r \sin\psi$;
- the ratio of the radii at the beginning and end of one turn is called design ratio τ; its expression is $\tau=\exp(-2\pi|a/r|)$, while it is constant for a log-spiral; unfortunately, as put in evidence in [8], little information has been published on the dependency of gain and pattern vs. τ, while it is believed that this parameter represents the most evident degree of freedom of our spiral structure.

In a two-arm spiral, modes +1 and –1 produce the same phasing of 0° and 180° at the feed points; all other odd higher order modes have the same phasing on the two feeds and this means that the spiral will radiate these modes efficiently if current flows on the arms where the spiral circumference is the same integer number of wavelengths. Assuming a perfectly balanced and phased feeding, even modes don't contribute significantly to radiation.
If the attenuation through the first active region is not large, then waves will go to the second ring region, characterized by a high-order radiation mode that superimposes on the main mode, and to third one, and so on. Frequency independence is then lost and the radiation pattern is not symmetric any longer and moves (or better, rotates) with frequency. It may happen that the spiral is so small that the higher-order ring doesn't exist, simply because it doesn't fit the spiral geometry; this happens clearly for the lower frequency values, but not for higher frequencies for which $f>3f_{min}$.

Another source of E-field distortion comes from reflected waves at the end of spiral arms (if they are not properly terminated) and this produces an additional term with counter-rotating polarization, because reflected waves are traveling in the opposite direction. The influence of these spurious radiation modes is synthesized in the axial ratio, the ratio of the maximum to the minimum value of the electric field (for a circularly polarized field in the absence of any distortion due to harmonic components or counter-rotating components the axial ratio is equal to one).
It is quite important to prevent propagation outside the active region and this may be accomplished by loading the ends of the arms, while accepting a slightly larger power loss. Loading on a balanced structure with ground plane reference quite far away may be accomplished with a series of shunt resistors that in principle should be placed on the outer ring (or a portion of it) close to the far (open circuited) end; in [11] several parallel resistors have been connected between the two arms, with the geometrical constraint that two portions of the outer ring on either arms don't correspond to the same angular position but are displaced by 180°.

The spiral antenna radiates symmetrically on both portion of space on the either sides with respect to antenna plane; for small size spiral antennas an absorbing cavity is usually placed to prevent backward radiation at the expense of a smaller effective gain. In the present case the use of a reflective ground plane is considered in order to increase forward radiation; the reflection of the ground plane excites some high-frequency modes farther away along the spiral conductors with some drawbacks on antenna bandwidth and axial ratio uniformity and must be counterbalanced by adjusting plane distance: some preliminary simulations showed inconsistent results for some plane positions (also between two simulators) and has justified the experimental activity.
Preliminary computer simulations on an archimedean spiral indicated that there is no need for τ close to 1, but, rather, τ in the order of 0.5 may be used to reduce weight and cost; results of this kind are rare in the available literature, as confirmed by Johnson [8], p. 14-14, and will be one of the issues of the experimental investigation.

Moreover, the beamwidth is a function of wave velocity and it increases with reduced *v*/*c* ratio, since proportionally the outer ring gets smaller with respect to wavelength. For a slow wave spiral antenna (with *v*/*c* in the range of 0.5) it can be shown that the input impedance *Z* gets larger for decreasing δ, which is our case since a self-complementary structure (featuring by definition δ=90°) of large size is impractical because of its weight and wind action, and also doesn't ensure a reduced *v*/*c* ratio. For δ<20° and *v*/*c* around 0.5, *Z* may be as large as 1000 Ω.
The reduction of wave velocity is also needed in order to "tune" the outer ring of the antenna to the minimum operating frequency given the required maximum size: λ=15 m @ 20 MHz in free space and with a maximum circumference of approximately 5 m, *v*/*c* must be around 0.3. In practice the outer ring circumference must be increased to account for a reduced number of turns (low wrap angle value) [3]: the looser wrapped log-spiral requires a larger outer diameter to achieve the same low-frequency axial ratio. For the archimedean spiral this issue is somewhat less evident since the constant spacing with respect to the constant ratio of the log-spiral reduces the diameter required to support the principal mode of radiation at the lowest frequency; given the preliminarily designed number of turns between 5 and 10, this implies a conservative reduction of *v*/*c* of only 20% to approximately 0.4, as confirmed by [3], where a 1.17λ circumference for a 10.5 turns archimedean spiral ensures an axial ratio of 6 dB.

III. Antenna implementation and first simulation results

The aspects or issues to be checked by simulations are outlined for clarity:
1) self-complementary antennas is often used as reference, but a wire antenna with wire radius much smaller than arm separation is used instead to reduce weight and manufacturing problems;
2) the outer radius is set by the minimum operating frequency (mOF), provided the real wave speed is known;
3) the inner radius is a more influent parameter, not only on the maximum operating frequency (MOF), but also on the overall antenna performance;
4) reflections at spiral ends and resistive loading;
5) gain improvement by ground plane and ground plane shape.

First, the influence of wire radius is difficult to evaluate, since most simulators introduce a given degree of approximation with respect to mesh elements geometry. For a low frequency antenna arms separation *w* is much larger than wire radius; in order to obtain appreciable influence it is expected that a strip must be used instead. This aspect is considered an open issue to be solved by extensive analysis of simulation results and simulators reliability and also of experimental outcomes. Second, wire radius has some influence on the values of the parameters of the transmission line formed by spiral arms and hence on wave velocity, so that it influences the outer radius.
Third, the inner radius may be set between 0.5*w* to 2*w* (*w* is spiral arm width) to verify by simulation the influence on antenna parameters: input impedance keeps stable around the theoretical 188.5 for 0.75*w* to 1.5*w*, while it exhibits unacceptable worsening below and above for shorter and longer values respectively, with significant reactive component.
Fourth, it is known that resistive loading of spiral arms improves VSWR and bandwidth at the expense of gain reduction in the lowest frequency interval around the minimum operating frequency. Resistive loading is in general added as distributed conductive material if the antenna is small size and built on dielectric material (such as a PCB antenna); in our case even the use of lumped elements is very difficult if the overall sie of the antenna and the distance of the grounded reference are considered.
Fifth, antenna backing is considered: in microwave mobile applications with integrated antennas an absorbing (lossy) cavity is used but there is no gain improvement; a conductive reflective plane as ground plane can increase antenna gain, but at the expense of deep oscillations. The interaction between ground plane and antenna may produce very different results (looking for example at the gain and VSWR) and is analysed for a) flat perfect electric conductor (e.g. a copper sheet), b) flat pec with increased magnetic permeability (e.g. a magnetic steel sheet), c) pec with conical shape, to keep a progressively reduced distance vs. frequency, corresponding to about a quarter wavelength distance, with respect to the supposedly active ring in the antenna [12].
For the hot issue of simulator choice and validation it is underlined that, with our attention on two main parameters such as input impedance and gain, a thorough comparison performed in-house with Feko, NEC2, Matlab code included in [17], and the results reported in [18], concerning a comparison of NEC4 with ASIA (Analysis Software of Infinite Arrays, from the same University) confirmed that large differences may be observed between fully tested and released to market products. Comparisons are made on stable values that for the input impedance are reached approximately one octave above the mOF: in the lowest part of the operating frequency range the input impedance is highly reactive with

several changes in sign of the imaginary part, and this reduces the available E-field level despite the good gain (that is a far field parameter, by the way). Related to this, some products cannot calculate and display results for near-field radiation that for the present application are of paramount importance.

IV. Experimental characterization

A 1.6 m x 1.6 m square wood frame has been built with wood supports in order to arrange a variable number of turns and spacing between turns, with the possibility of placing the feeding balun in the center. The frame is positioned horizontal with respect to lab floor suspended by wood columns at the desired height from the reflective ground plane (RGP), that lies on the lab floor (that complements and extends somehow the RGP itself). The E-field intensity is read with a large bandwidth E-field meter, suspended to a mast and to a variable length wood arm to explore different heights and different positions in the horizontal plane. The antenna is fed by an RF amplifier in order to get a meaningful amplitude of the E-field and correspondingly a reading error within probe specifications.

A. Flat vs. conical ground

As shown in [18] the behavior of flat and conical reflective grounds seem opposite and complementary, in that a flat ground has a flat gain curve at the maximum values reached by the conical ground curve (that features large oscillations), but the VSWR exhibits the same amount of oscillations for the flat ground and a remarkably higher value (see above at the end of Section III the behavior of the input impedance, directly related to that of VSWR).

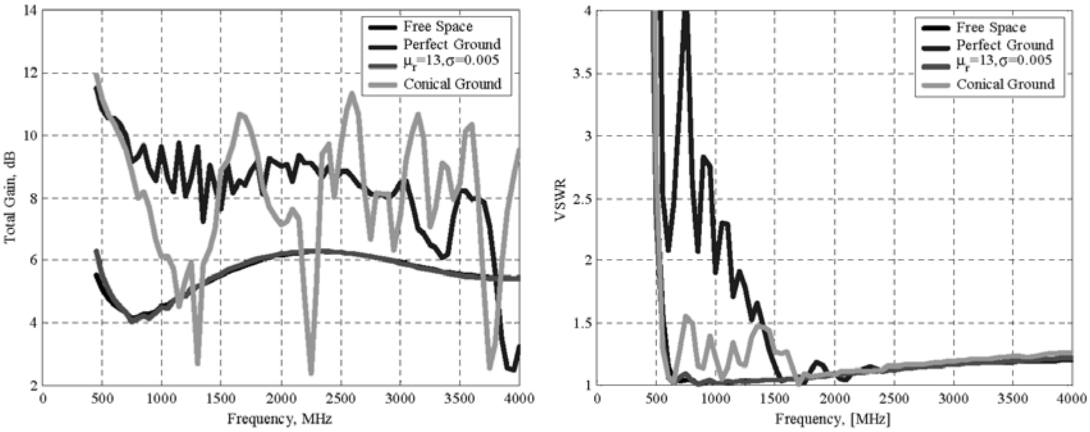

Figure 1. Gain and VSWR for flat and conical ground on a reduced size spiral

Still, the oscillations that characterize the conical ground gain are to be explained. The author believes that a solid ground plane (in numeric simulators it is always represented by a wire mesh) can attenuate the problem. In order to control the VSWR oscillations of the flat ground, it was found that a shorter distance from the antenna may help with a compromise with the radiation pattern uniformity.

B. Measurement results of a 8 turns 1.60 m x 1.60 m spiral

A preliminary test setup was built as shown in Fig. 2. Different number of turns and arm width values are possible, as well as different positions of the underlying ground plane; tests with the conical ground plane cannot be done directly on this setup for size and weight reasons, but on a scaled prototype.


Figure 2. Spiral antenna frame for lab tests

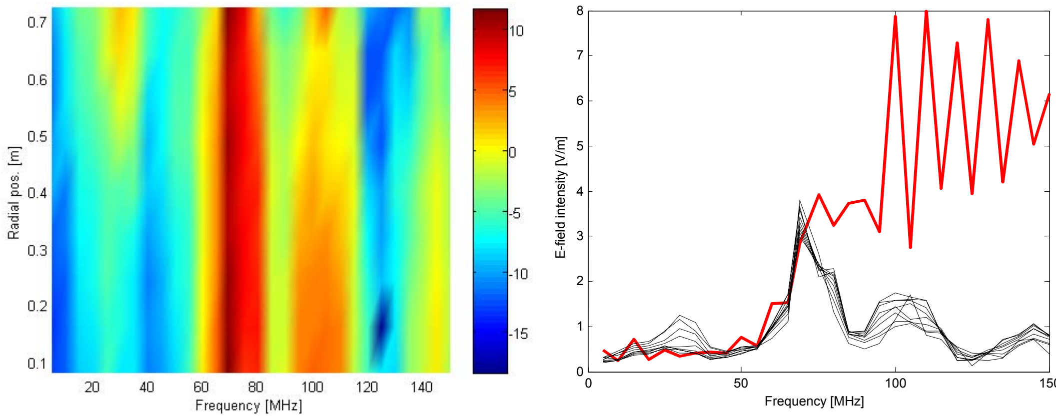

Figure 3. (left) measured electric field at 1 m from spiral plane and
(right) comparison with simulations (Feko at 28 cm, in red)

The results of a first series of measurements and of the comparison with simulation data are shown in Fig. 2. The simulator is fed by the voltage
It is evident that the simulator produces wrong results above 90 MHz and maybe the values right before this interval are influenced by this unexplained behavior.

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