System Design and Assessment Notes

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SYSTEM LETHALITY: PERSPECTIVE ON HIGH POWER MICROWAVES

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Abstract

Once a high power microwave (HPM) weapon has been demonstrated to successfully produce effects on a particular system, there remains the problem of ascertaining what that success really means. One would like to believe that a test that shows damage or disruption means that systems similar to the tested system are vulnerable as well. Unfortunately, *similar* is not well defined in this context and it is very difficult to define *electromagnetic similarity in lethality* rigorously. This paper attempts to define some parameters for electromagnetic similarity and provide some guidelines on extending our ability to define lethality classes. This process begins with some examples in which systems are shown to be different and continues to define some of the tools and data requirements that might be used to more rigorously define these limits.

I. INTRODUCTION

There have been many exposures of systems to high power, high frequency electromagnetic waves. Some of these exposures have resulted in damage or disruption of the system of interest. These examples form the basis for the idea of a high power microwave (HPM) weapon. To have a viable weapon, one must go significantly further than this, however. When a user fields and exercises such a weapon, he expects the weapon to be effective against classes of systems that are a threat to that user. In few cases is the test object on which the lethality condition is based actually in the set of weapons that is a threat to the user. In a lethality experiment, a successful test only means that the particular HPM weapon is effective against that particular target in that particular situation (a field test, even an elaborate one, is an inexact simulation of a real event, not an example of a real event). It takes more information from theory and experiment to extend the applicability of the completed tests to a useful class of systems. A predictive capability is required. That capability is a physical predictive model (the model may be semiempirical, but it must contain some additional physical information) that enables an interested scientist to extrapolate from a known test data point in an as yet undefined multidimensional space to another point that represents a real situation.

The first step is to examine the data (points) that represent the original point of departure. There are a number of ways in which that simulation is not quite accurate. Some of the departures will matter and some will not. Examples of departure from the *real* case might include the presence of the ground, the range, the pulse train used, the relative orientations of test object and the source, and, perhaps most importantly, the test object itself will differ from the threat object.

It is clear that the threat test object will usually differ from the object under test. It is not clear, however, how much of a difference matters. In Section III we will consider some simple examples that would change the lethality conclusion if small changes are made in the system itself. It is surprising how little change may be required.

Systems vary from test object to test object for a variety of reasons. Typically, threat systems are improved throughout their operational life. From an electromagnetic point of view, they also degrade from wear and chemical changes. Maintenance often changes the electromagnetic character of the systems. Finally, the systems change in their geometry (and therefore in their electromagnetic topology) as they are operated.

A model for predicting weapon effectiveness must be able to deal with all of these variations in the system as well as departures from the actual threat example in the simulation or technology demonstration. In general, a strictly numerical approach is not adequate because of the extreme detail with which one must model a real system. Strictly statistical models based solely on the observation that systems fail in a particular simulation are limited because strictly statistical models are not valid beyond the data set on which they are based [Schmidt and Launsby, 1988].

With these limits, how does one succeed? In the past, a number of communities have attempted to solve this problem and have failed. The source region electromagnetic pulse (SREMP), the system generated EMP, and EMP communities all attempted to produce a system model. In each case, they succeeded in relatively simple representations of the systems, but failed (often badly) for the real systems.

There are three new developments available which may help us succeed in developing a predictive capability today for portions of the problem, where large and well funded communities have failed in the past. These are:

A. Topological decomposition
B. Statistical electromagnetics
C. Massively parallel numerical methods for electromagnetics

Each of these will be more fully developed in Section V, and some critical limitations reviewed.

II. SIMULATION FIDELITY

Baum [1992] used the simple diagram of Figure 1 to look at the source to system transfer function for HPM interaction.

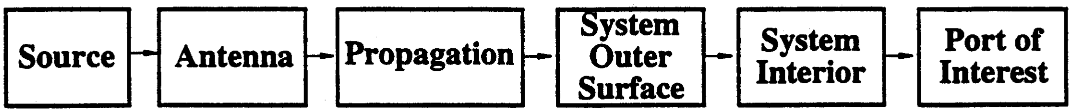


Figure 1. Factorization of transfer function from source to system.

When conducting tests to establish lethality of a particular HPM weapon, the first step is a proof of principle type experiment. While, as noted above, this experiment does not establish lethality for the class of systems desired, it does provide the point of departure for establishing lethality for the class later. The point can be considered a point in n-dimensional space in which the dimensions are the independent variables describing the possible source to port-of-interest interaction. Description of the source deserves some comment.

In HPM interaction the source waveform or wavetrain can be chosen to produce maximum reaction of the system of interest. The waveform may be chosen using a number of different norms and other characteristics to establish the desired reaction. A norm is a simple descriptor of a property of the waveform. The peak electric field, peak time derivative of the electric field, and square root of the power density are all norms that might be of interest for lethality. The pulse duty factor, pulse repetition rate, and pulse modulation will also impact the lethality of the incident radiation. Each of these must be considered when determining the simulation fidelity. Each characteristic of the incident Rf radiation should be considered a separate dimension in the n-dimensional space describing the test.

An antenna is, in some sense, part of the test establishing lethality. Its characteristics are important if the incident wave can vary across the target system or if it changes the frequency spectrum of the transmitted signal. For example, if the incident wave can properly be described as a plane wave, then the antenna characteristics may not be important for narrow band sources.

Propagation of the electromagnetic wave from antenna to system is usually free space propagation in the user's problem, but is often more complicated in the simulation. Reflections from nearby objects, including the ground, complicate the environment at the system. If the source is sufficiently powerful, then the nonlinear dissipative effects of the atmosphere must be considered. Similar (but perhaps different) factors will apply to the "real" case.

The simulation (tested) system should be as close in design and performance to the target system as possible. As will be considered in more detail below, the simulation system may differ, perhaps substantially, from the "real" system. For most simulations, it is desirable to include a means for measuring the system response. Of course, addition of probes and the like changes the system geometry and therefore the response. Insertion of the probes is an engineering trade-off between what we learn from the experiment and its fidelity. The overall problem for particular simulation conditions is represented in Figure 2.

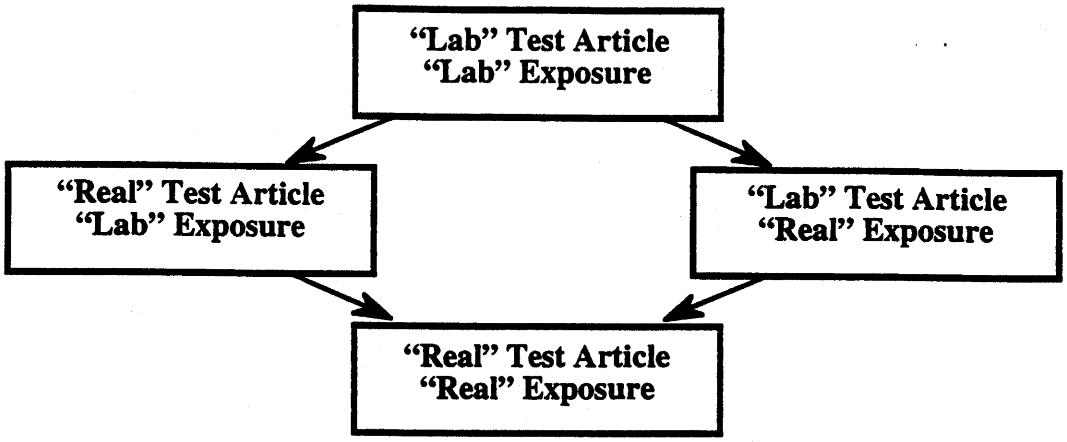
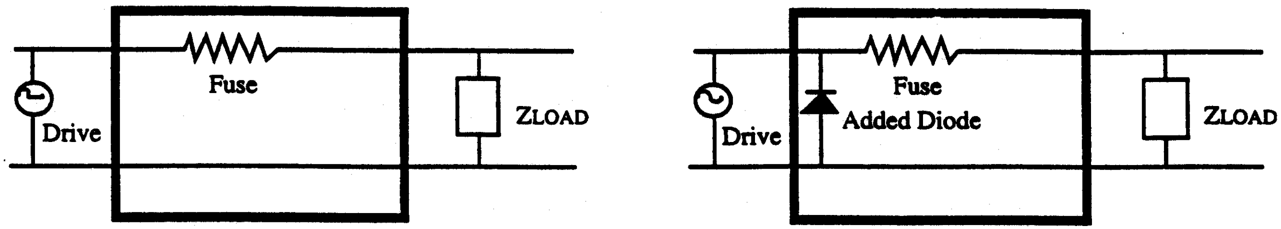


Figure 2. Problem Summary

III. HOW SYSTEMS DIFFER IN TOPOLOGY AND CONSEQUENTLY VULNERABILITY

An F-16 is clearly different from an M1A2 tank. No one would assume that finding an HPM weapon that was effective against an F-16 would imply that same weapon was effective against the tank. But, what dividing line can we use that will separate the systems that are like the system of interest from those that have a different behavior from a lethality standpoint? That answer is difficult to find, but we can give some examples of systems that behave differently with only minor changes. The first example is that of Figure 3.



3.A Basic Circuit

3.B Circuit With Added Component

Figure 3. A simple system that is then modified by the addition of a diode.

The left part of Figure 3 shows a very simple system that consists of only a fuse. That fuse fails by the deposition of thermal energy in the fuse and the metal in the fuse melts. One can easily construct many of these systems, test each of them, and develop a statistical model that will allow us to describe the statistics of the set of tested systems. These systems can be said to be *alike* from a lethality point of view, because they fail in a similar way. The right drawing shows the same system with a diode added. This addition may have a profound effect on the susceptibility of the system. Values of the diode can be chosen so that the diode fails early and short so that there is a net reduction in the energy required to induce failure in the system. It can also be chosen to conduct at values above the failure levels for the fuse and therefore protect the fuse. Either of these is considered a change in the failure mechanism. A much more interesting difference lies in the parameter used to describe the failure mechanism. Diodes can fail because of peak voltage rather than deposited energy. Therefore, not only is the required energy deposited for failure very different, but the figure of merit required to measure it is also different. In terms of the n-dimensional space described above the failure falls along a different axis from the levels of the original system. Designing a test matrix that considers all of these mechanisms for failure can severely increase the cost of a lethality test. These two systems are clearly different in the sense of this discussion, even though they differ only by the addition of one semiconductor component, and could appear identical from a functional and external physical appearance point-of-view.

Another, somewhat more complex example begins with a missile. Consider that we have tested this missile and caused it to fail. We have examined the test data and found the failure point as well as the entry point for the energy causing the failure. It is then simple to add a filter (perhaps a capacitor) for that entry point and to change the required incident power to produce failure by orders of magnitude.

These are two simple examples. For complex systems there are many such possibilities. We can see the difficulty from these two examples, however. Small changes in very complex systems can change the failure levels and modes dramatically. If the tested system is different, in any such way, from the system encountered in the application, predicting failures based on the tested system results is very difficult. The major uncertainties will often be dependent upon the information available to the modeler (including past experience), not on the model capabilities.

IV. WHY SYSTEMS DIFFER IN VULNERABILITY

We have mentioned that systems typically under test are often different than the systems ultimately of interest. There are some convenient examples of how the changes might happen. Consider the diagram of Figure 4.

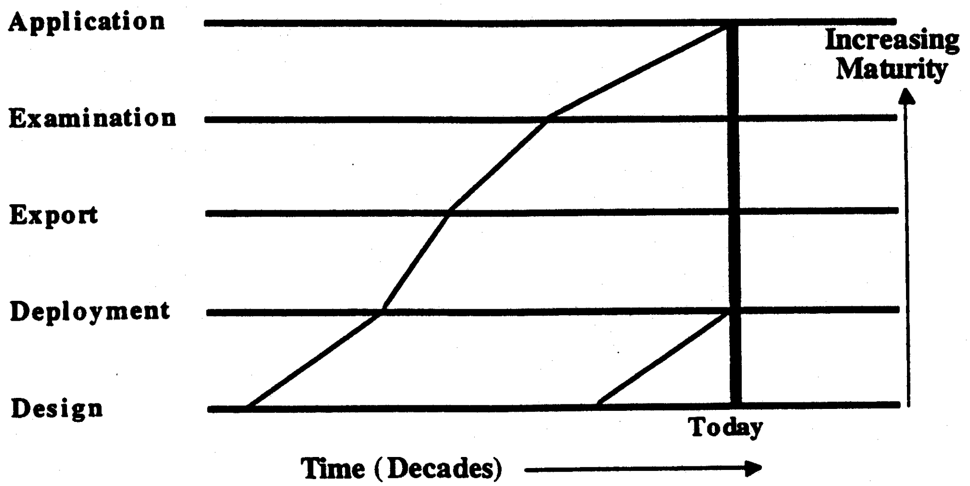


Figure 4. Evolution of systems we might test to those we might face.

A system that we test today usually comes to us by a circuitous route. After its design, the system was deployed. After use as a top-of-the-line system and its capabilities were well known, it was sold to some secondary user. Since the value of the system is lower, it is likely to be available for test. Also, operators of systems are not usually anxious to have their systems tested to any electromagnetic threat (EMP, HPM, EMC, etc.). The system of interest, on the other hand, is often one which has just been fielded. There are potentially tens of years between the design of the new system of interest and the availability of such a system for testing. Often there are several generations of electronics during that period.

Other mechanisms for fundamental change include maintenance and evolutionary changes in the system. Systems typically change state as they are operated (different functional modes). Some may even change their basic geometry. For example, an open cargo door can change the shielding topology of a system substantially.

V. NEW DEVELOPMENTS FOR IMPROVED PREDICTIVE CAPABILITIES

There are three developments which can help us succeed in areas which have not been possible in the past. These are topological decomposition, statistical electromagnetics, and massively parallel electromagnetics codes. These each offer an opportunity to improve the predictions of electromagnetic stress placed on sensitive components of the system. Limitations due to knowledge of the actual effects of these stresses on the system are addressed at the end of this section.

Topological Decomposition: Baum [1990] describes the details of this method of breaking a system into smaller less complex parts. This division requires that the ways that electromagnetic energy can flow between subsystems also be included in the model. These 'tubes' that carry the energy into and out of the subsystems are very general. They can represent a wire, a transmission line, a waveguide or other general means of energy flow. Drivers for the systems can be point sources or extended sources can be modeled by careful construction of the proper integrals. A detailed description of a decomposition of parts of the EMPTAC aircraft is shown in Parmentier, et.al. [1993]. The basic methodology and rules of topological decomposition were first developed in Baum, Liu and Tesche [1978]. Predictions of stresses at points within the system matched experiments very well (in some cases the match was within a fraction of a dB). A criticism that has been offered of this work is that too much information about the system is required to get good results. Unfortunately, this problem applies to all solution approaches; the problem of predicting the vulnerabilities of real systems is difficult and requires a lot of effort to get good results. The Parmentier work [1993] is the best to date (of which the authors are aware) in terms of analytical stress predictions matching experiments on test geometries that resemble real systems. Many of the required parts of the topological decomposition and the electromagnetic analysis required for this problem are contained in the ARES code [Yang, et.al., 1992].

An issue for application of this approach is the actual electromagnetic topology of the system of interest. If it has been constructed with a well-defined topology, then application is straight forward, given sufficient design information. If the system does not have a good electromagnetic topology, then benefits will be quite limited.

Statistical Electromagnetics: The complexity of predicting the response of a real system has driven a number of researchers to use statistical methods in the formulation of the problem. Miller and Lehman [1993] laid out a rationale for the development of this subject. They point out that most attempts at solving the electromagnetic response (stress at a point) of a complex system have been deterministic in nature. There are many degrees of freedom associated with these problems which hinder our ability to perceive the problem correctly. The complex nature of the problem suggests that an approach using statistical methods closely coupled with Maxwell's equations is an appropriate way to solve this problem. Statistical mechanics is a very successful analog that shows promise of the method.

It should be noted what is meant here by statistical electromagnetics. In this case, it is a careful combination of statistical methods with Maxwell's equations. Equations of motion and state for a plasma may be included as well. Statistics derived from counting failures have little value in this context, since the applicability of the use of the statistics does not extend beyond the data.

This area is largely one of basic research at this point. However, there have been some beginnings. Lehman [1993] describes the distribution of modes in an overmoded cavity. The complexity of the cavity is ill defined and this work is a long way from the application to a system. Wheluss [1994] suggests a number of basic research topics for this area. Other examples of nonlinear scattering problems may transition to chaos [Reichl, 1992]. Various attractors may appear in the solutions, but those calculations have not yet been made for this application.

Massively Parallel Electromagnetics Codes: New numerical methods have shown large improvement recently in their ability to treat large detailed systems [Fulmen 6, 1993]. Unfortunately, we are far from being able to treat real systems in their entirety. We are also unable to completely specify systems. So our limitations track. These codes can, however, treat limited subsystems that result from topological decomposition so they are still very useful in this application. This capability is, so far, unable to do the entire problem, but is clear that the number of problems that can be treated has increased substantially since the work done in the 1970's for the various EMP communities.

Some Critical Limitations: There are two basic limitations which can limit the ability to perform vulnerability analyses for systems.

The first has been discussed and involves knowledge of the system design. This includes the system physical design, the electromagnetic topology, and the functional design.

The second is central for the evaluation of the production of effects at the circuit/component level in the system (given the calculation of stress using the methods noted above), and involves identification of the specific components and their design (primarily for damage) and the circuit operating voltages/currents, clock rates, frequency pass-bands, etc. (primarily for upset, jamming, and interference). High fidelity testing is usually required to evaluate these susceptibility levels since analysis has most often not been found adequate for this purpose. Susceptibility level variations from item to item will be significant for some components, while for others they may be quite limited. A knowledge of these variations will be required for high-confidence predictions.

Limitations in knowledge in either of these areas will limit the certainty of predictions using any tools (and perhaps even the ability to make any meaningful predictions).

VI. CONCLUSIONS

We have presented some of the issues for system lethality predictions in high power microwave research. Many of these issues impose limitations at this stage of the research, reflecting the fact that there are limitations on both knowledge of the systems and current modeling capabilities. The types of knowledge needed to define the modeling problem have been reviewed, and suggestions for potential improvements to modeling capabilities have been presented. Work to improve each of these areas will be required to support development of modeling tools which can be used with confidence to predict the effective lethality of modern HPM weapons on threat systems.

Requirements for analyses in support of hardening and survivability programs also present significant challenges, but are easier in some ways that vulnerability problems. For example, there is usually a more complete knowledge of the system, and all or portions of the system can be tested to determine stress levels required to produce effects. The improvements discussed in Section V would also support this work.

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