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TITLE

HARDENING AGAINST A COMBINED ELECTROMAGNETIC THREAT

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Hardening against a Combined Electromagnetic Threat

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1. SUMMARY

Hardening against the electromagnetic environment is usually done by considering each threat separately. In recent years, there has been an increasing interest in methods for unifying electromagnetic standards and procedures to simplify the design and testing of hardening techniques. This approach is appealing as it could reduce the cost of system design as well as the cost of testing.

The objective of this paper is twofold: firstly, to assess the feasibility of combining the various electromagnetic threats to simplify the design of electromagnetic protection; and secondly, to assess the feasibility of using a single test, or at least a minimum number of tests, to verify the electromagnetic hardness of a system.

2. PREFACE

Today's platforms rely heavily on electronic subsystems to perform their mission. The newer technologies used in modern systems are often more susceptible to intentional or unintentional electromagnetic threats, while the electromagnetic environment has become more complex and severe. These threats cover frequencies from DC to 10's of GHz, and include high power microwaves (HPM), nuclear electromagnetic pulse (NEMP), lightning (LEMP), electrostatic discharge (ESD), licensed transmitters and general electromagnetic interference (EMI). The success of the missions now depends on the proper protection of the critical subsystems against any threat which may be encountered during operations.

Over the past decades, techniques were developed for hardening against the various threats, but as they all obey the same Maxwell's equations for propagation and coupling, a single hardening philosophy started to take shape, namely the use of zonal shielding in addition to penetration protection. Although simple, this concept has become costly and inefficient because the procedures of hardening against each threat were developed independently and resulted into standards and survivability steps particular to each threat.

In recent years, there has been an interest in methods for unifying electromagnetic standards and hardening procedures to simplify electromagnetic design and testing [1]. Benefits would include reductions in costs and time to design, implement and test the required hardening as the result of fewer standards and handbooks and by the avoidance of test redundancies.

3. A UNIFIED APPROACH TO ELECTROMAGNETIC PROTECTION

Conceptually, this approach consists of simply combining the various electromagnetic threats together, propagating them along paths representing the various forms of coupling or filtering, and then comparing the residual levels with the susceptibility thresholds of the individual sensitive components. This approach is particularly well suited to be used along with the concept of electromagnetic topological decomposition [1]. Topological decomposition subdivides a problem into a set of volumes (or localized areas) through which the electromagnetic energy propagates and surfaces through which it penetrates [2] [3]. Although simple in concept, some of the characteristics of the individual threats and coupling functions, as well as the device failure mechanisms have an important impact on our evaluation of whether a system will survive or not. For this reason, it is necessary to discuss the following aspects separately : the electromagnetic environment (EME), the coupling mechanisms, the device failure modes and the simulation of the threats.

The environment is defined by overlaying all the electromagnetic threats across all frequency bands. But, as discussed in detail below, it is necessary to subdivide them into two categories: wideband and narrowband emissions. It is also often the case that a given threat may be specified with some parameters that may vary within some limits. For instance, a narrowband emission may be defined by specifying a range for its carrier frequency or a wideband impulse by a range for its rise time and duration. To be really useful, a design method should allow for such a type of specification.

The coupling mechanisms of the EME may take many forms, such as coupling through intentional receptors (antennas), currents induced in cables, coupling through shielding barriers and apertures, etc. They can usually be approximated by simple transfer functions. As with the EME, they need to be classified as either wideband or narrowband. They may also be specified with some varying parameters (within specified limits).

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The propagated electromagnetic signals reaching sensitive components may upset or permanently damage them. In order to properly estimate the system susceptibility, it is important to understand how this energy interacts with electronic components to cause failure.

Once a system is designed and built, it is necessary to verify its hardness but this process is often costly. Therefore, combining some of the EME to reduce the number of tests is attractive. However, this may also result in over-testing the system which may make it impractical in most cases.

A new method for predicting the response of a system to an electromagnetic threat is presented below. This discussion concentrates on the theoretical background of this method, identifying its limits, and suggests an alternate method for describing, combining and propagating electromagnetic signals. It aims at the following goals:

- To keep the error below design margins (typically 10 to 30 dB) — Errors introduced by the approximations are generally less than 10 dB.
- To allow narrowband signals or transfer functions to be specified across a frequency range.
- To readily obtain time-domain parameters such as peak value, rise time, duration, energy, etc., from the frequency domain.
- To allow comparison against failure thresholds in various forms (level-sensitive, power-duration dependency, etc.).
- To allow the computation of optimal shielding based on failure thresholds.

4. FAILURE MODES IN ELECTRONIC SYSTEMS

It is important to understand how the electromagnetic energy is causing equipment damage and upset. Electromagnetic signals can be described in terms of several physically significant parameters which may include the total energy of the signal, its peak value, its duration or its maximum rate of change. The physical mechanism causing failure usually depends primarily on one or two of these parameters. Also, for a given device, the failure mechanism may be different depending on whether upset or damage is considered. The discussion below shows two possible definitions of the threshold curves, one based on a level sensitivity and the other on a power-duration (energy) relationship.

The upset threshold is defined as the minimum signal that will cause a system malfunction, but for which no permanent damage or degradation occurs. Upset thresholds are typically level-sensitive, that is an upset will occur anytime a signal exceeds the threshold, given in volts or amps. This threshold may be frequency-dependant, hence dependant on the transient duration. Most, if not all, of the EMC design methodologies described in various textbooks are based on level thresholds [4] [5].

The damage threshold is defined as the minimum signal that will cause permanent damage or degradation. This is often the result of an elevated temperature causing meltdown due to the energy deposited by the pulse. For instance, many authors [6]-[8] have related the power a semiconductor may safely absorb to the pulse duration. For short pulses, the energy is deposited adiabatically and failure is determined solely by the total energy content of the pulse. For longer pulses, some of the heat dissipates to the surrounding medium resulting in more power being tolerated before breakdown. For even longer pulses, a steady-state regime is established and the failure level becomes related to peak power instead of total energy. A good model based on the thermodynamics of semiconductor junction meltdown was developed by Wunsch and Bell [6]:

$$P_f = \frac{A}{T} + \frac{B}{\sqrt{T}} + C \qquad (1)$$

which relates device failure with the power (P_f) and duration (T) of the applied signal. This type of interaction is not usually taken into account by the classical EMC methodologies.

5. DEFINITION OF ELECTROMAGNETIC QUANTITIES

Most electromagnetic analysis are performed in frequency domain. Furthermore, the phase information is usually not known or difficult to obtain, therefore only the magnitude of the Fourier transform is used. The magnitude is in "/Hz" units and a relation can be found between this function and some time-domain parameters, such as peak value, rise time and duration. For instance, the peak of the magnitude function is not by itself an indication of the peak in time domain, but if multiplied by the bandwidth of the signal, a good approximation may be obtained. The rule-of-thumb that the response of a system is proportional to its bandwidth is well accepted, but may yield to erroneous results, especially when the distinction between wideband and narrowband signals is lost.

White in [5] for instance combines all electromagnetic ambient threats by merging all wideband sources (in V/m/Hz), converted into their equivalent field strength (in V/m), and all narrowband sources, already described by their field strength. Conversion to field strength is done by using a bandwidth adjustment factor applied to every frequency band. This in fact is equivalent to multiplying the spectrum by $\omega/2$. While this approach is apparently widely used, no theoretical proof is given to support it and no guidelines are suggested with respect to its domain of validity. Our work shows that White's approach may give results which are wrong by several orders of magnitude in the cases of narrowband interactions.

One of the reason why this generally used method fails for narrowband interactions is that the bandwidth information of the signals is not kept. To overcome this problem, a distinction needs to be made between wideband and narrowband electromagnetic quantities (signals or interactions), where narrowband is defined as a quantity demonstrating some resonant features. Wideband quantities are described by a function corresponding to the magnitude of their spectrum, denoted by H(f). In the method proposed, narrowband quantities are described by two discrete values, denoted by $\hat{H}(f_r)$ and $BW_H(f_r)$, corresponding to the peak magnitude and bandwidth at the center frequency. Note that the magnitude $\hat{H}(f_r)$ represents the peak amplitude in <u>time domain</u> for signals or the maximum coupling (at the center frequency) for interactions. By extension, the magnitude and bandwidth may be described by a function, still denoted by $\hat{H}(f_r)$ and $BW_H(f_r)$, which shows the valid range where such an electromagnetic quantity may occur. Alternatively, the bandwidth may be derived, if not specified, from other parameters such as the resonance factor (Q), damping coefficient (z) or duration (T), which are related to one another as:

$$\frac{BW}{f_r} = \frac{1}{Q} \ , \quad Q = \frac{1}{2z} \ , \quad BW \approx \frac{1}{T} \qquad (2)$$

The last expression is not very accurate (±10 dB error) and should be avoided to obtain the bandwidth. Wideband and narrowband signals may be combined separately to form two distinct composite signals, which may be further propagated or compared against the predefined failure thresholds. From theoretical and numerical analysis, we can summarize how a signal E(f) or $\hat{E}(f_r)$ is propagated through a transfer function H(f) or $\hat{H}(f_r)$ with the following interaction matrix:

Wideband signal / wideband interaction:

$$R(f) = E(f) \cdot H(f)$$

Wideband signal / narrowband interaction:

$$\hat{R}(f_r) = E(f_r) \cdot \hat{H}(f_r) \cdot 2\pi \, BW_H$$

$$BW_R(f_r) = BW_H(f_r)$$

Narrowband signal / wideband interaction:

$$\hat{R}(f_r) = \hat{E}(f_r) \cdot H(f_r)$$

$$BW_R(f_r) = BW_E(f_r)$$

Narrowband signal / narrowband interaction:

$$\hat{R}(f_r) = \hat{E}(f_r) \cdot \hat{H}(f_r) \cdot \frac{BW_R(f_r)}{BW_E(f_r)}$$

$$BW_R(f_r) = \min(BW_E(f_r), BW_H(f_r))$$

where R represents the response. R(f) denotes a wideband response while $\hat{R}(f_r)$ and $BW_R(f_r)$ represent the magnitude and bandwidth of a narrowband response. This matrix shows why the standard definition of composite threat as given by White [5] fails when subjected to narrowband interactions. In those cases, the response does not depend on the $E \cdot \hat{H}$ or $\hat{E} \cdot \hat{H}$ product alone, but also depends on the bandwidth. Note also that wideband signals may become narrowband as they are propagated.

5.1 RELATING TIME AND FREQUENCY DOMAINS

Electromagnetic problems are usually worked out in frequency domain but the failure thresholds are generally specified in terms of time-domain parameters (such as peak value, total energy, etc.). It is therefore of utmost importance to relate those parameters with the frequency-domain spectrum.

With our representation of fields, the peak value in time-domain of narrowband signals is stored and thus obtained directly, and other parameters such as duration or energy may be derived easily from the bandwidth. This relation is not obvious for wideband signals, but it can be proven that for single pulse-type signals, the maximum of the function $H(\omega) \cdot \omega$ is a very good approximation of the peak value of signals in time-domain. This can be easily shown analytically for simple problems, such as for the double exponential, or numerically for more complex problems. For any given spectrum, there is an infinite number of waveforms whose spectrum will approximately fit it, and that may exhibit widely different time-domain characteristics. In particular, it is always possible, for a given spectrum, to choose between high-intensity short signals and lower-intensity longer-duration signals. The estimates obtained from the $H(\omega) \cdot \omega$ product are reasonably accurate for pulse-type signals, ie. signals which concentrate most of their energy into a short burst. Furthermore, the $H(\omega) \cdot \omega$ product identifies the portion of the spectrum that contributes the most to the time-domain function. It can be used to identify the two cutoff frequencies α and β (the -3 dB points below and above the frequency of the maximum) which contribute the most to the signal duration and rise time respectively. The rise time, pulse width and duration may be estimated as $t_r = 2.2/\beta$, $t_w = 0.7/\alpha$ and $t_d = 2.3/\alpha$ respectively. In general, better accuracy is obtained if the curve fits underneath a trapezoid whose sides are steeper than ±20 dB/decade, but reasonable estimation may be obtained as long as a top portion of the curve can be identified.

5.2 COMPARING RESPONSE AGAINST FAILURE THRESHOLDS

As discussed in previous sections, the failure threshold is defined by the particular physical mechanism involved. The level-sensitive thresholds are the simplest as a failure occurs as soon as the signal reaching the component exceeds the threshold, although that threshold may be frequency-dependant. A simple model of upset threshold for various logic families is shown on Figure 1, which clearly shows that larger transients are necessary to produce upset above the operating speed of a given family. Narrowband signals R(f) at the susceptible component are simply compared against this threshold for all frequencies while the product $R(\omega)\cdot\omega$ is used for comparison for wideband signals. Note that this method is implicitly used by White [4] [5]. Any excess above the threshold curve also represents the additional shielding required to properly harden the system against the threat.

As introduced earlier, other models may be better suited to define the threshold curve. For instance, the Wunsch and Bell model expressed by Equation (1) is more accurate to predict permanent damage in semiconductors. It may be approximated in terms of voltage or current in the form:

$$V_f \approx \frac{A}{\sqrt{T}} + \frac{B}{\sqrt[4]{T}} + C \qquad (3)$$

which is shown on Figure 2 for standard TTL logic family. The threshold may also be expressed in terms of bandwidth:

$$V_f \approx A\sqrt{BW} + B\sqrt[4]{BW} + C \qquad (4)$$

This threshold can be used directly to compare against narrowband signals. This threshold may be constant if the duration or bandwidth of the signal is constant over its frequency range.

It has been shown that the $H(\omega)\cdot\omega$ product can be used to locate the α cutoff frequency and by using $T \approx 0.7/\alpha$, we obtain:

$$V_f = A\sqrt{\alpha} + B\sqrt[4]{\alpha} + C \qquad (5)$$

and by using $\alpha = 2\pi f$, the $H(\omega)\cdot\omega$ product may now be compared against the threshold. The signal will not exceed this threshold if its $H(\omega)\cdot\omega$ curve lies completely underneath the threshold curve. This is illustrated on Figure 3.

6. THE USE OF COMPOSITE THREAT FOR TESTING

This section presents some considerations about the feasibility of using one or more composite tests to verify the electromagnetic hardness of a system. To qualify as a valid test, a composite waveform must satisfy some basic criteria. Firstly and most importantly, it must guaranty that if a system survives the composite test, it will then survive any of the constituent threats. A composite test is always a form of overtest and thus, there is no guaranty that a system will survive the composite test even though it survives all the individual threats. Therefore the second criterion is that it should not grossly overtest the system. Finally, the composite waveform should be realizable.

To properly verify the hardness of a system or subsystem, it is necessary to consider it as a 'black box'; that is to assume nothing about how the signal propagates to reach the sensitive components and how it interacts with the components to cause failure. Designing a test (ie. a composite test waveform) based on some assumptions made about a particular type of interaction or failure mode will result in a test that may fail to detect some electromagnetic incompatibilities if some of the assumptions are wrong.

6.1 COMPOSITE WAVEFORMS BASED ON ADDITION OF SPECTRAL COMPONENTS

Adding all individual threats together ($\Sigma e(t)$) would unquestionably result in a composite test that would adequately test the system. Unfortunately, the exact definition of some threats is not always known, but rather defined by some parameters which vary within some limits. Using the superposition property of the transform, $\Sigma e(t) \leftrightarrow \Sigma E(f)$, the problem can be solved in frequency domain instead. The various threats are not synchronous, therefore taking the maximum of all spectra (or the envelope of the possible spectra if a threat has some varying parameters) instead of adding them defines the spectrum of the composite test. A composite test waveform could then be defined in the time domain. It would seem that any waveform whose spectrum meets or exceeds this composite spectrum would be adequate, but as it will be shown in the example below, some aspects of the system such as particular failure modes may dictate the choice of the composite test waveform. Another problem with this method is that the magnitude of the spectrum is proportional to the duration of a signal (as stated by the time/frequency scaling property of the Fourier transform), yielding to a composite test of very high amplitude. One possible solution is to limit the pulse length to the thermal time constant of the system components.

A simple example will be used through this section to illustrate the discussion. It is an attempt to design a composite test waveform for testing a system according to the CS116 specification of MIL-STD-461C [9]. CS116 specifies a series of damped sinusoid waveforms to be injected at every point of entry. The normalized waveform (peak current I_P=1), shown on Figure 4 (top), is defined as:

$$I_0\, e^{-2\pi f_c t/Q} \sin(2\pi f_c t) \qquad (6)$$

for frequencies from 10 kHz to 100 MHz with a peak amplitude which is frequency-dependant as shown on the bottom. I_{MAX} is 10 A for Army and Navy procurement and 5 A for Air Force procurement. The corresponding spectrum (for I_{MAX}=1) at some frequencies covering the whole possible range is shown on Figure 5, along with the spectrum of two different composite tests considered. The first is a double exponential, defined as:

$$A(e^{-\alpha t} - e^{-\beta t}) \qquad (7)$$

which corresponds in this example to a pulse of 22 A peak amplitude and 0.3 μs duration. The second composite is a frequency-modulated dual sweep (first sweep at constant amplitude up to 1.4 MHz followed by a second sweep, decaying as 1/t, up to 100 MHz), in the form:

$$A_1 \sin(\gamma_1 t^2)\Big|_{t<60\mu s} + A_2 \frac{\sin(\gamma_2 (t-t_0)^2)}{t}\Bigg|_{t>60\mu s} \qquad (8)$$

which corresponds to a signal of much longer duration (150 μs) and lower peak amplitude (1.2 A).

It is clear from this example that a given spectrum may translate into waveforms having very different characteristics, although they have the same energy. The energy (normalized in 1 Ω) of a real signal e(t) is related to the magnitude of its spectrum by:

$$E_t = 2\int_0^\infty |H(f)|^2 \, df \qquad (9)$$

from which we may deduce that the energy of the composite test is necessarily larger than any of its constituents. The energy of the two composite tests here is about 40 μJ, which far exceeds the energy of any of the individual CS116 tests (0.5 nJ to 0.7 μJ depending upon the frequency). It is clear that the composite test constitutes a severe overtest of the system. It is conceivable in this case to build such a source (220 A peak amplitude and 0.3 μs duration for the maximum CS116 specification), but in many cases, it becomes completely unrealistic. For instance, the generator to test for all HPM threats of 1 kV/m and 1 μs duration in the 1-10 GHz band would need to produce a field of 30 MV/m in 10 ps!

If the total energy was the only physical parameter of concern for failure, then we could generalize that any waveform whose spectrum matches the composite would adequately test for all threats at once. Unfortunately, we have seen that failure is often related to other parameters such as peak value and duration. Many waveforms with identical spectrum, thus of comparable energy, will have widely different time-domain characteristics as illustrated by our example above.

Table 1 below summarizes the response of systems of various frequency bands (both wideband and narrowband) to the CS116 waveform (at the maximum resonance) and to the two composite tests. It is clear that the dual FM sweep is not a valid test waveform as it results in smaller responses under some conditions. The system may be underexcited by a factor of as much as Q, the resonance of the interaction. Therefore, failure modes based on a level-sensitive threshold will not be tested appropriately. Also, the responses to this composite are of much longer duration, therefore, failure modes based on power-duration thresholds may not be tested appropriately either. In general, an impulse waveform such as the double exponential tends to concentrate all the energy into a short burst of higher amplitude and shorter duration. Both the level-sensitive and power-duration thresholds failure modes will be tested correctly, but at the expense of overtesting the system and difficulty of design of a suitable source.

Interaction		Peak response to test waveform (A)		
f_c (Hz)	Bandwidth (Hz)	CS116	Double exponential	Dual FM sweep
wideband	4M	1.01	19.78	1.22
1M	1M	0.91	6.85	1.03
1M	100k	0.38	1.25	0.87
1M	10k	.049	0.14	0.21
20M	20M	0.90	10.69	.096
20M	2M	0.49	1.84	.081
20M	200k	0.12	.22	0.066

Table 1. Peak response of various systems to CS116 standard test and two composite test waveforms.

The general conclusion reached from this discussion is that it is not sufficient for a composite pulse to have the same spectral amplitude as the sum (or worst case) of all the threats, but also that some of the time-domain parameters be respected. In particular, it is important that the pulse duration is consistent with the real threats as failures based on a power/duration relationship are very common. An extreme and obvious example is a train of N pulses whose spectrum is comparable to the spectrum of a single pulse of N times the amplitude.

6.2 COMPOSITE WAVEFORMS BASED ON PEAK AMPLITUDE

An alternative method for designing a composite test was described by Podgorski ([10] [11]) who suggested to combining narrowband fields (given in peak time-domain units) with the $H(\omega)\cdot\omega$ product of wideband fields in a fashion similar to the procedure used by White [5] for design and analysis. The result is then considered as a $H(\omega)\cdot\omega$ product, whose maximum gives the peak value of the composite, and the -3 dB cutoff frequencies give the duration and rise time. What this method fails to take into consideration are the effects of the resonant nature of the threats and/or interactions. In our example, it results in a composite pulse of similar shape and duration (0.3 µs) but with an amplitude 13 times smaller (1.7 A instead of 22 A). Although this reduces considerably the overtest, it results in an undertest in high-resonance situations. That should also be obvious when considering the energy of this composite (0.23 µJ in this example) which is less that some of the constituent threats (up to 0.7 µJ). Another example (HPM threats in the 1-10 GHz band) revealed undertest situations by 2-3 orders of magnitude.

7. CONCLUSION

To properly design and verify the electromagnetic hardness of an electronic system, it is important to understand the failure mechanism of its electronic components. The two most common failure threshold models were described: one based on level sensitivity and the other based on a power/duration (or level/duration) relation. The conventional methods for EMC/EMI design already use some of the concepts of composite tests implicitly. It is not always understood that these methods are limited to problems involving level-sensitive failure thresholds only and for which no resonant interactions are present.

A new method for EMC/EMI design and analysis was presented. All threats and interactions along a given path may be combined, but a distinction between wideband and narrowband signals and interactions is always preserved. It also allows the definition of narrowband threats or interactions over frequency bands. A simple interaction matrix was presented to model the propagation of electromagnetic signals under various conditions. Simple algorithms for obtaining important time-domain parameters, such as peak value, rise time and duration, were given. Most importantly, these results may be compared against failure threshold curves (level-sensitive or power/duration) to either calculate a failure index or obtain the optimal additional shielding required to harden the system.

This method may be a very valuable design tool for hardening against multiple threats. However, extreme caution should be used when transposing these results to obtain a composite test waveform for testing. First, a composite test should guaranty that a system will survive any of the threats if it survives the composite test. This implies that the composite test should never undertest the system under any of the normal conditions. It was shown that, based on the energy content, the composite test waveform is a considerable overtest of the system, which would increase the cost of a system if it had a requirement to meet this test. That would be contrary to the prime objective of the whole concept, which is to reduce overall hardening costs, and would not be acceptable by the manufacturer. It was shown that the design of a composite test based on the magnitude of the spectrum alone is not sufficient. Waveforms of same spectrum may have widely different time-domain characteristics, particularly peak value and duration. It may result in a composite test which severely overtests the system under most conditions but may still undertest it under some specific interaction. It was found however that impulse signals such as the double exponential may provide an adequate test, but can be a considerable overtest. In addition, although it is theoretically possible to define a composite test for any problem, in most cases, this proves to be impossible to realize in practice. It may require fields or currents 10 to 1000 times larger than normally required, usually of extremely short duration.

It is concluded that the scope for developing a single electromagnetic simulator for evaluating the hardness of systems against all wideband and narrowband threats is extremely limited. The reason for this is that system upset and damage involve complex physical processes and that no single physical parameter, such as total energy or peak value, is sufficient to determine if failure will occur. To ensure that a system is tested properly, it is not only sufficient that the composite pulse has the same spectral amplitude as the sum of all the threats, but also that some of the time-domain parameters be respected, particularly peak value and duration.

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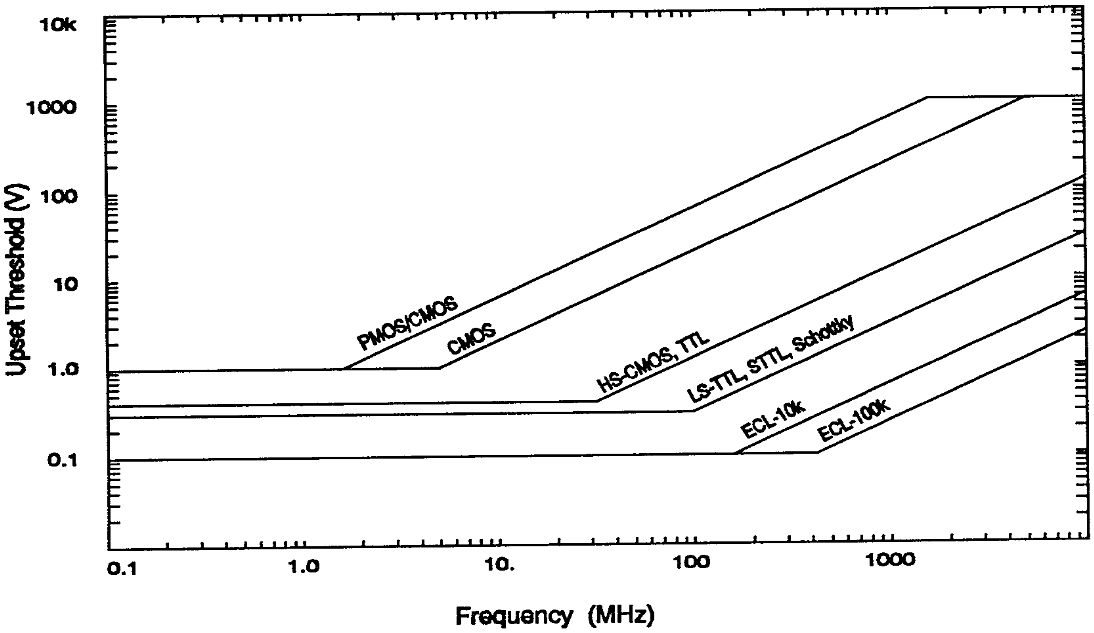

Figure 1. Upset threshold for various logic families.

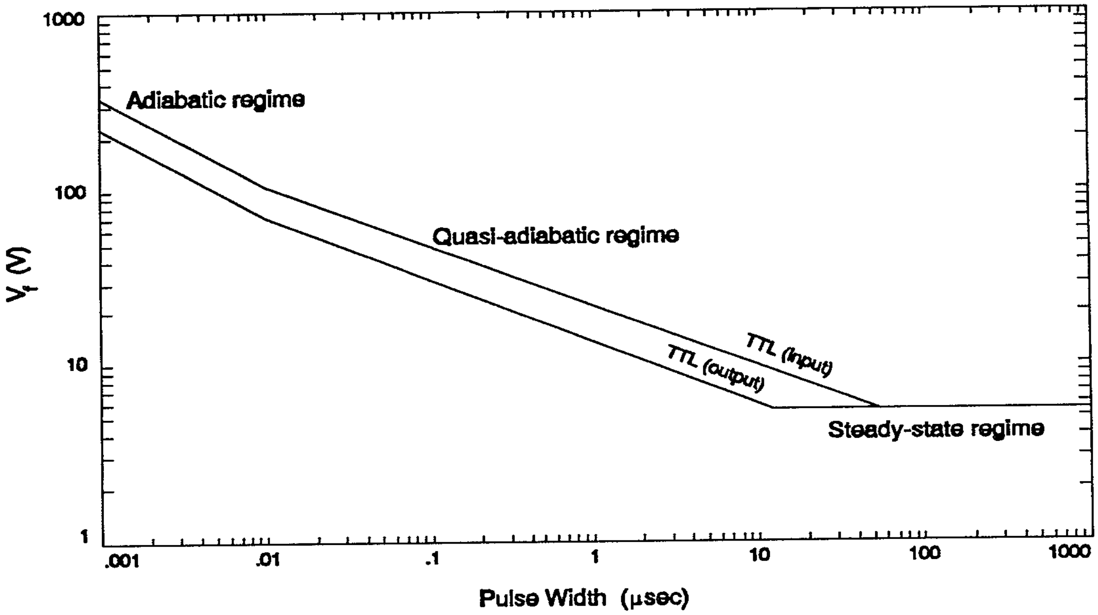

Figure 2. Damage Threshold for TTL logic family.

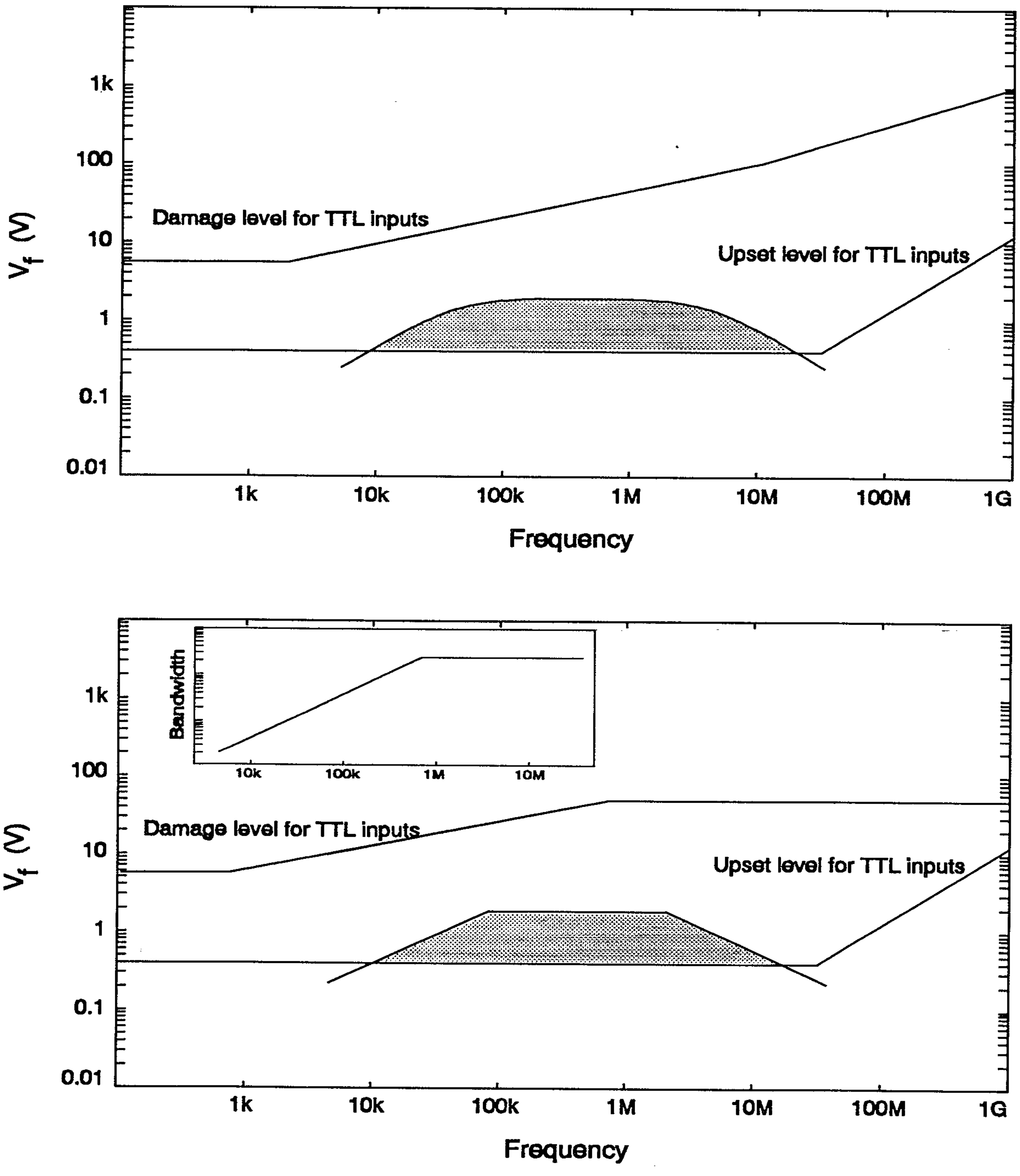

Figure 3. Example of upset and damage threshold comparison of wideband (top) and narrowband (bottom) signal.

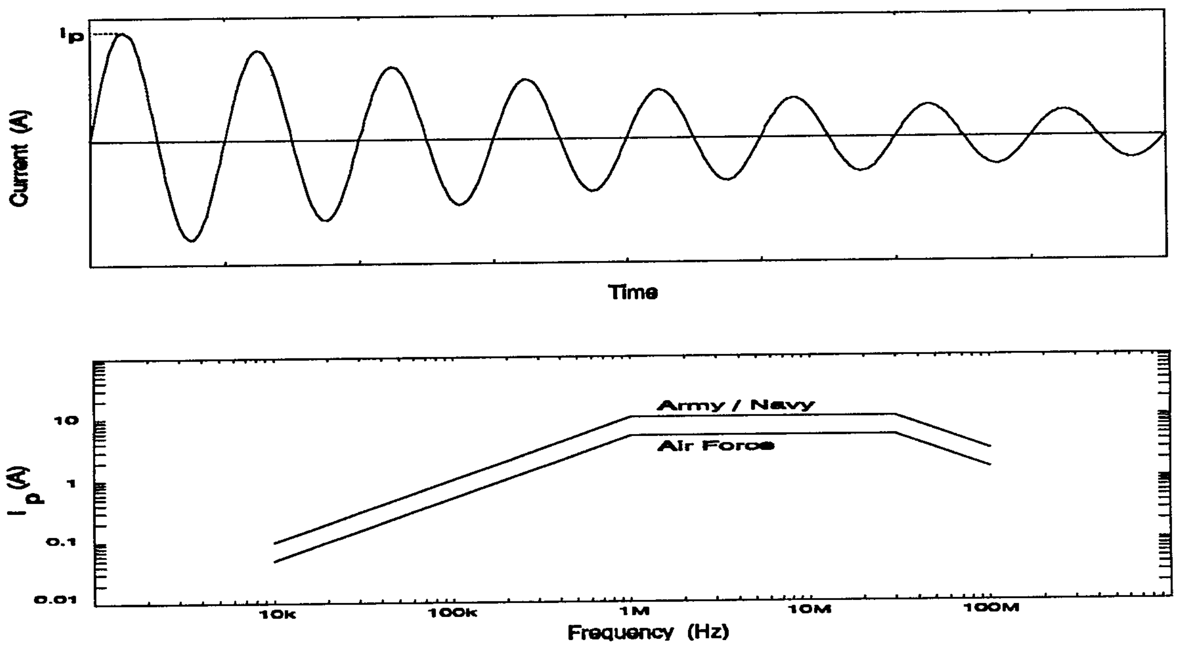

Figure 4. CS116 current injection waveform specification.

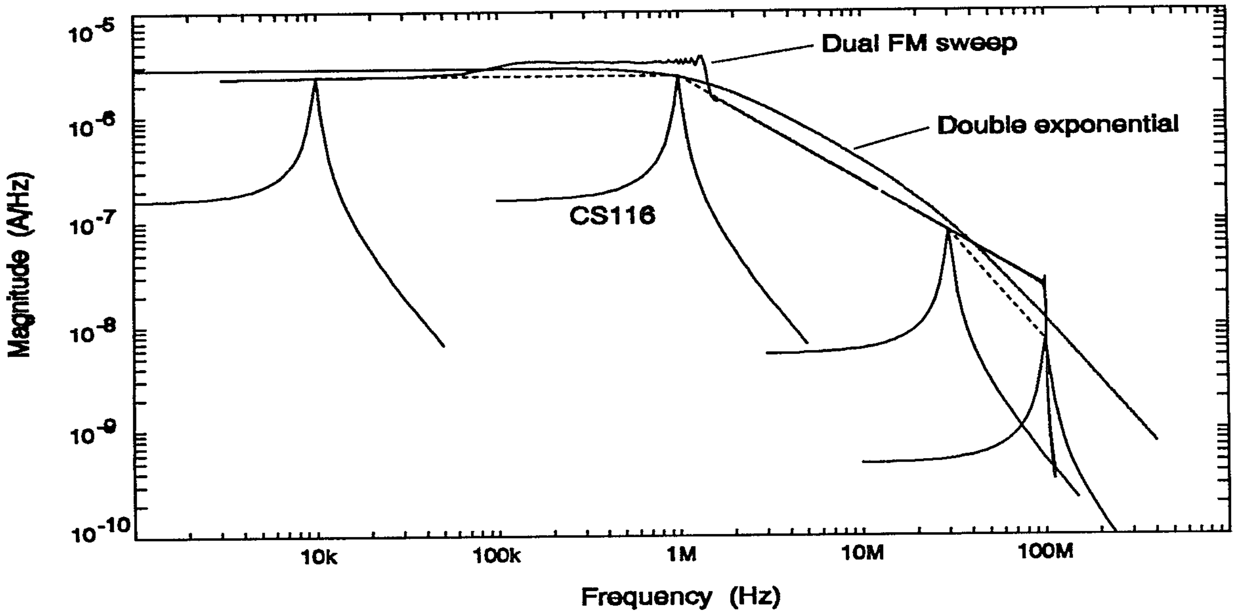

Figure 5. Spectrum of CS116 and two composite waveforms.