

Phase Processing Techniques for the Prediction of Induced Current

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Abstract—This paper reviews the currently used minimum phase algorithm approach for the prediction of induced current as a result of the incidence of a time domain electromagnetic environment such as an Electromagnetic Pulse (EMP). An alternative to this approach is proposed that enables the user to identify a lower bound on the minimum phase prediction. The technique has been applied to over 500 transfer functions with three different High Power Electromagnetic (HPEM) environments and the results are presented and discussed within this paper.

Index Terms — Electromagnetic Pulse, Phase, Signal Processing, High Power Electromagnetic

I. INTRODUCTION

WHEN dealing with the evaluation of platforms against High Power Electromagnetic (HPEM) environments, full scale, full threat trials can be expensive to conduct and time consuming thus being prohibitive. Low level techniques have been used for many years by the civil and military aircraft clearance community to overcome the requirement of testing platforms using full threat HPEM simulators. Portable measurement systems further simplify testing by allowing on-site HPEM tests, reducing time and cost requirements. However, making good aircraft magnitude *and* phase measurements is a slow and difficult process, especially without proper calibration of the site, which may be near an active runway or other encumbrance. For this reason, transfer function measurements are restricted to magnitude only. The transfer function magnitude measured for cable bundles or looms of interest are used to predict induced current for an incident HPEM environment. The accepted methods for this process rely on a Minimum Phase Algorithm (MPA) to generate the phase associated with the magnitude-

only transfer function. Limitations of this technique are discussed within this paper and a new method for associating a lower bound prediction with the MPA result is presented and discussed.

II. THE MEASUREMENT OF TRANSFER FUNCTIONS

A. Low Level Swept Current (LLSC)

Aircraft cable bundle transfer functions can be measured using the Low Level Swept Current (LLSC) technique. This technique was developed in the 1980s by those seeking to remove the need for high power illumination of aircraft during the process of providing aircraft clearance evidence against High Intensity Radiated Field (HIRF) environments [1]. LLSC involves illuminating an aircraft with a uniform electric field of approximately 1V/m. The aircraft is illuminated from four orientations in turn and completed for two polarizations of the transmit antenna. The technique is generally conducted between 500kHz and 400MHz and measurements are split into three bands to maximize transmit antenna efficiency and to ensure sufficient resolution in the final transfer function. The technique can be used up to 1GHz but validity of the transfer function at these higher frequencies is dependent on the length of the cable bundle being measured and the position of the current probe on the bundle affects the final result.

The first stage of LLSC is to measure the incident (reference) field. The second stage is to measure the induced current in the cable bundle of interest whilst the reference field is illuminating the aircraft. The final stage involves the processing of the measurements such that a transfer function is generated. The LLSC technique results in 24 data files for each cable bundle (three bands, two polarizations, and four orientations) all of which have been normalized to the measured reference field.

Initially, the data is frequency tied such that 8 files remain (two polarizations and four orientations). In some cases (as will be discussed later), the processing stops here resulting in polarization and orientation dependent transfer functions for each cable bundle measured. However, for the case of frequency domain HIRF testing, a generic transfer function is calculated which is the highest measured coupling for any frequency; these transfer functions are polarization and orientation independent. Generic transfer functions introduce an inherent safety-margin in to the resulting equipment susceptibility assessment. This susceptibility assessment,

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known as Bulk Current Injection (BCI) is not addressed in this paper. Polarization dependent but orientation independent transfer functions can also be obtained if required.

The resulting transfer function is expressed in terms of current per incident field ($\text{dB}\mu\text{A}/(\text{V}/\text{m})$).

A typical LLSC set-up is shown in Fig. 1. Typical LLSC transfer functions are shown in Fig. 2 and an extrapolated generic is shown in Fig. 3.

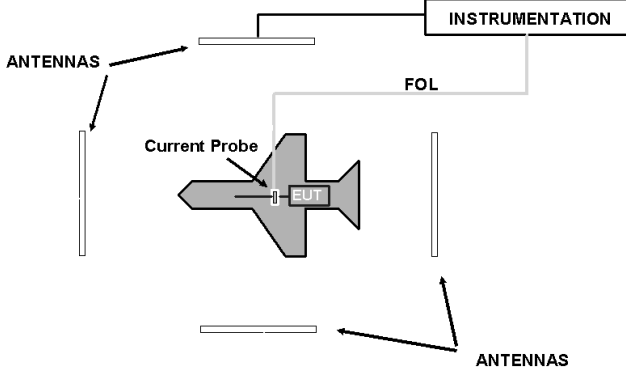


Fig. 1. A Typical LLSC Set-up. Four antennas are used to illuminate the aircraft with a low level (typically $< 1\text{V}/\text{m}$) E-field for two transmit polarizations (horizontal and vertical).

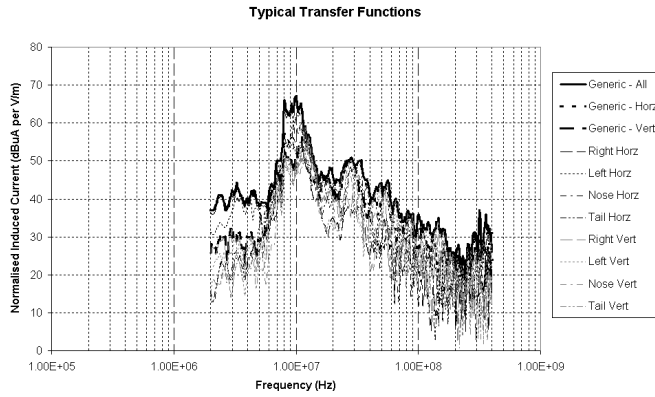


Fig. 2. Typical LLSC Transfer Functions. The measured transfer functions can be both polarization and orientation dependent, or generic as either polarization dependent or independent. The solid lines show the generic transfer functions.

III. PREDICTION OF INDUCED CURRENT

The measured transfer functions can be used to predict an induced current as a result of an incident HPEM environment. In the case of frequency domain HPEM environments, the transfer function can simply be extrapolated to the environment as it is expressed in terms of the incident electric field. However, for time domain HPEM environments, the prediction is complicated by the lack of phase information and convolution is required instead of simple extrapolation. Phase is not measured during the LLSC technique due to difficulties concerning the accuracy of phase at frequencies above the dominant frequency and the effect of current probe location on the cable bundle being measured. The lack of phase information is mitigated by the use of the Minimum Phase Algorithm. This algorithm generates phase for the measured transfer function by imposing minimum phase constraints. The constraints are that the resulting prediction is stable, causal [2] and has a stable inverse. Although the minimum

phase response will not be the response of the system [3], it provides an order of magnitude response based on the total energy content of the wave being concentrated towards $t=0$. However, specific information such as the peak value, its location and maximum rise time may not be adequately predicted for reasons given in Section IV.

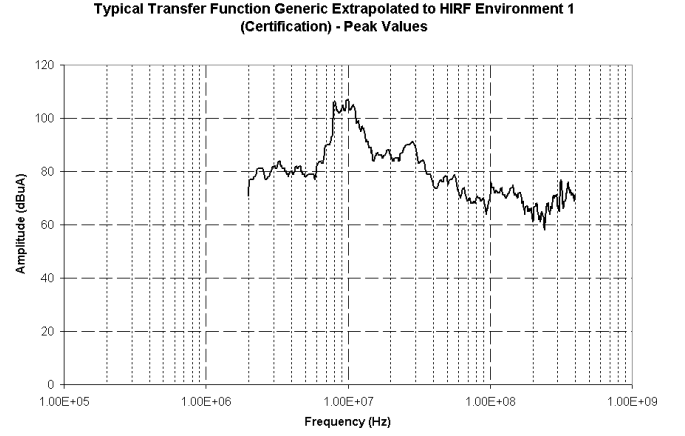


Fig. 3. Typical Transfer Function Generic Extrapolated to HIRF Environment 1 (Certification) – Peak Values [4]. The generic transfer function can be extrapolated to create a limit line for susceptibility assessment using Bulk Current Injection (BCI) techniques.

A. The Prediction Process

The prediction process is described below

The discrete prediction of the LLSC waveform in the time domain from partial information in the frequency domain is possible. The minimum phase can be reconstructed from magnitude only data if one assumes the signal is causal, i.e. if $f(t) = 0$ for $t < 0$, then the minimum phase can be reconstructed using complex cepstrum analysis [2]. The minimum phase response requires that the zeros of the transfer function lie in the left half of the s -plane ($s = \sigma + j\omega$ with $\sigma < 1$) or alternatively inside the unit circle of the z -plane ($z = e^{js}$ and $|z| < 1$). It can easily be shown that minimum phase can be obtained from the Hilbert transform of the log magnitude of the LLSC sequence, i.e.

$$\angle f(\omega) = H[\log |f_c(\omega)|] \quad (1)$$

Where $H[\cdot]$ is the Hilbert transform. The threat waveform $f(t)$ is usually given in the time as a measured waveform with known amplitude and phase or as an analytic minimum phase function. A Fourier transform (FT) of the threat waveform provides the magnitude $|f_t(\omega)|$ and phase $\angle f_t(\omega)$ data in the frequency domain. The minimum phase LLSC transfer function is then convolved with the threat waveform under the usual assumption of a linear, scalable time invariant system.

$$f_{c*}(\omega) = [|f_c(\omega)| + \angle f_c(\omega)] \times [|f_t(\omega)| + \angle f_t(\omega)] \quad (2)$$

An Inverse Fourier Transform (IFT) is performed on the convolution complex frequency domain output resulting in the

predicted cable bundle response, $f_{c*}(t)$.

The process can be repeated with all measured transfer functions and can be used with any in-band HPEM environment including Ultra Wideband (UWB), High Power Microwave (HPM), Damped Sinusoid (DS) and Electromagnetic Pulse waveforms such as Nuclear EMP (NEMP), High-altitude EMP (HEMP) or Lightning EMP (LEMP).

The use of the MPA to construct phase is favored by the EMC community using the resulting data to determine the response of the aircraft to an incident HPEM environment. The primary reason for this is that the MPA will generally over-estimate the induced current that would be observed if that HPEM environment was incident on the aircraft.

B. Example

A typical aircraft magnitude-only measured transfer function is shown in Fig. 4. This transfer function has an artificial 20dB per decade roll-off from 1.6 MHz to 10 kHz. This corresponds to the condition that the platform length $\leq \lambda/10$. This is a technique used by the aircraft EMC community to overcome poor measurement sensitivity at the lower frequencies [4].

The transfer function has been convolved with the IEC EMP waveform shown in Fig. 6. The transfer function and the frequency domain EMP waveform are overlaid in the frequency domain in Fig. 7. Finally, the predicted current is shown in Fig. 8 (time domain) and Fig. 9 (frequency domain).

Transfer Function of a Typical Air System

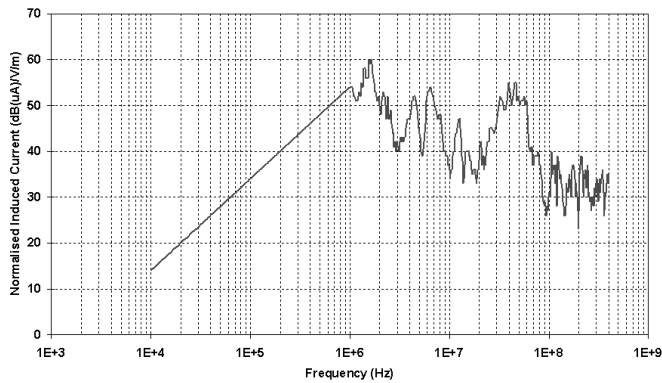


Fig. 4. Transfer Function of a Typical Air System. The transfer function has a 20dB/decade roll-off below 1MHz to overcome poor measurement sensitivity at low frequencies. The transfer function has a dominant resonance at 1.6MHz.

IEC 61000-2-9 Early-time EMP Waveform

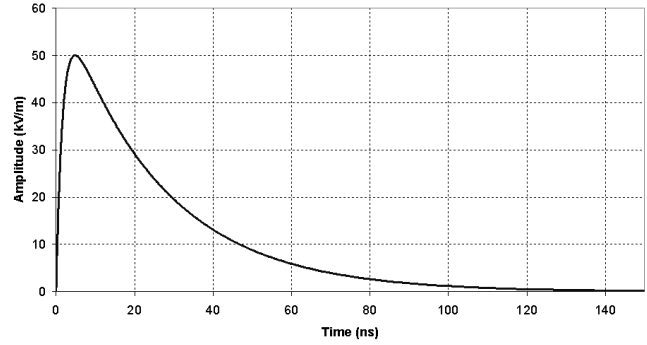


Fig. 5. IEC 61000-2-9 Early-time EMP Waveform. This waveform is the HPEM environment used for this example.

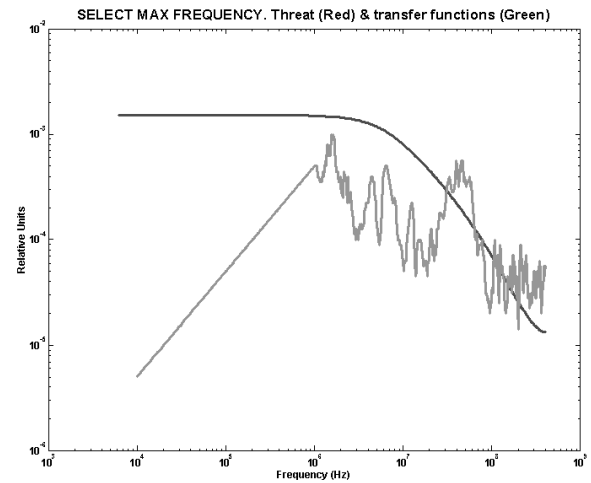


Fig. 6. Convolution Process. The transfer function is overlaid with the Fourier Transform of the HPEM environment.

Predicted Current after Convolution with IEC 61000-2-9 Early-time EMP Waveform

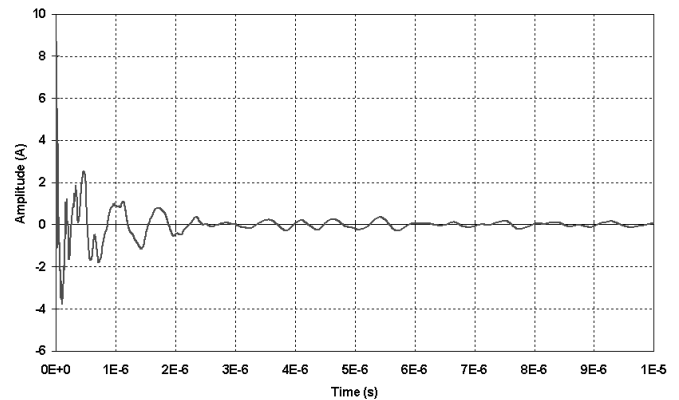


Fig. 7. Minimum Phase Prediction – Time Domain. The result is a predicted peak current of 9.7A.

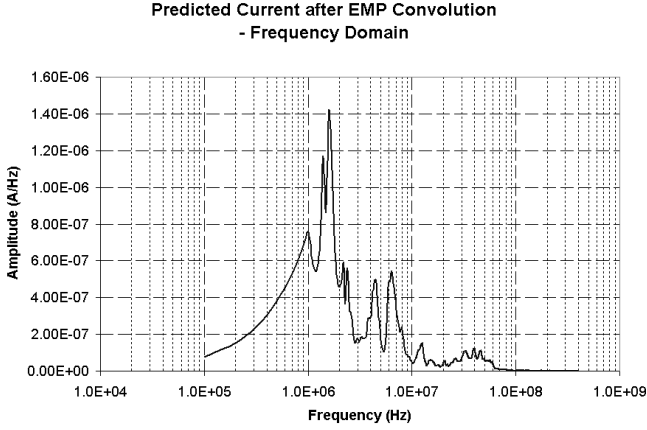


Fig. 8. Minimum Phase Prediction - Frequency Domain. The dominant frequency of the transfer function (1.6 MHz) also dominates the predicted current due to the shape of the HPEM environment in the frequency domain.

C. Limitations

Although the MPA provides one realization of a credible induced current for a measured magnitude, the question often arises as to whether it over-estimates the response of the system to the given HPEM environment, impacting on the ability of the system to be cleared to a specific HPEM environment.

A simple alternative to the MPA is to use a network analyzer to measure the phase of the system along with the magnitude of the coupled current. However, it is not always practical to transport the test object to a well characterized facility (for example the ELLIPTICUS [5] antenna facilities in the U.S.) where valid phase measurements are possible. The validity of the measured phase is therefore often called into question, as it is highly dependent on several factors including interaction between the transmitting antennas and test environment, impedance changes in the cable bundle being measured (current probe location), proximity of nearby objects, the test configuration and the electromagnetic properties of the ground over which the measurement is performed.

IV. NEW METHOD

It is useful to develop an alternative lower bound that can be associated with the predicted MPA current. In order to generate this lower bound, a minimum peak algorithm has been developed. The origin of the problem with the minimum phase algorithm arises because the phase reconstruction from magnitude only data is not a unique solution. If the system is not minimum phase (i.e. when some of the zeros of the transfer function may lie in the right half-plane) then (1) does not hold. Most radio-frequency systems exhibit a non-minimum phase response and the cepstrum approach given in (1) cannot be used reliably to obtain the practical non-minimum phase realization. The linear deviation in phase is due to a pure time delay (dispersion) in the time domain. The effect on the predicted impulse response is not to change the magnitude of transfer function but modify the phase response in some linear way. A new algorithm is proposed which is

similar to the previous algorithm with regard to the evolution of the threat waveform and its convolution with the complex LLSC transfer function. The only constraint on obtaining the non-minimum phase response is to force causality on the system by again initially obtaining the minimum phase response. The all pass filter representation of $f_c(w)$ is used

$$f_c(w) = f_{\min}(w) \cdot H_{\text{all}}(w) \quad (4)$$

Where $f_{\min}(w)$ is the minimum phase form of $f_c(w)$. From (1),

$$f_{\min}(w) = |f_c(w)| \exp(jH(\log(|f_c(w)|))) \quad (5)$$

and $H_{\text{all}}(w)$ is the infinite impulse response of an all pass filter [1].

$$H_{\text{all}}(w) = \prod_{m=0}^{P-1} \frac{z - d_m}{1 - d_m^* z} \cdot \prod_{n=0}^{Q-1} \frac{(z - b_n^*)(z - b_n)}{(1 - d_n^* z)(1 - b_n z)} \quad (6)$$

Where d_m is a real pole-zero of the all-pass filter, b_n is the complex pole-zero of the all pass filter and b_n^* is the complex conjugate. The optimisation search is reduced to a $2P+2Q$ dimensional search.

Pole-zero pairs are then fitted to this transfer function using the iterative Steiglitz-McBride method [6]. Complex-conjugate zero-pairs are then flipped outside of the unit circle on the z-plane varying the contributing phase component. This modified transfer function is then convolved with the HPEM environment of interest and the inverse Fourier transformed to obtain the result. This is performed for all combinations of pairs – for example a model consisting of 4 pairs yields 15 possible combinations.

The result of this process is a predicted current based on minimum phase variations such that the results are causal, realistic and stable.

A. Results

The transfer function shown in Fig. 5 has been processed by both the traditional minimum phase algorithm and the new minimum peak algorithm using firstly the IEC 61000-2-9 Early-time EMP waveform and secondly a 20MHz Damped Sinusoid waveform. For this example, 8 permutations of the minimum peak algorithm were required for the EMP waveform and 4 permutations were required for the 20MHz Damped Sinusoid waveform. The minimum peak of these permutations is discussed here. Fig. 11 and Fig. 12 show the minimum peak and minimum phase results in the time domain and frequency domain respectively for the EMP waveform. Fig. 13 and Fig. 14 show the minimum peak and minimum phase results in the time domain and frequency domain respectively for the 20MHz Damped Sinusoid waveform.

Comparison of Minimum Peak and Minimum Phase Results
IEC 61000-2-9 Early-time EMP

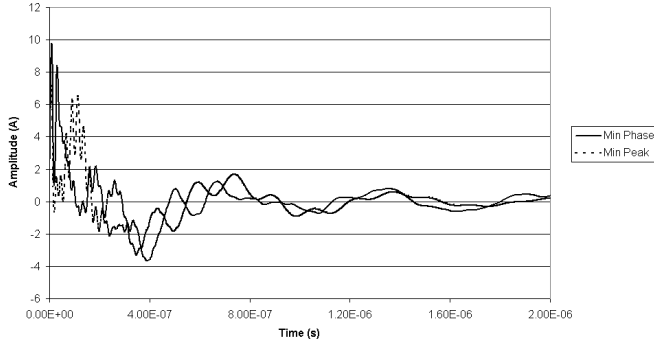


Fig. 9. Minimum Phase Result Compared with Minimum Peak Result – IEC 61000-2-9 Early-time EMP. This graph enables a comparison in the time domain between the results of the traditional minimum phase algorithm and the new minimum peak algorithm.

Comparison of Minimum Phase and Minimum Phase Results
20MHz Damped Sinusoid

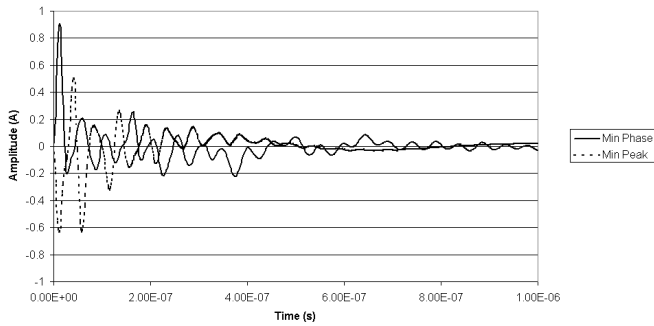


Fig. 10. Minimum Phase Result Compared with Minimum Peak Result – 20MHz Damped Sinusoid. This graph enables a comparison in the time domain between the results of the traditional minimum phase algorithm and the new minimum peak algorithm.

Minimum Peak Results Compared with Minimum Phase Result
IEC 61000-2-9 Early-time EMP

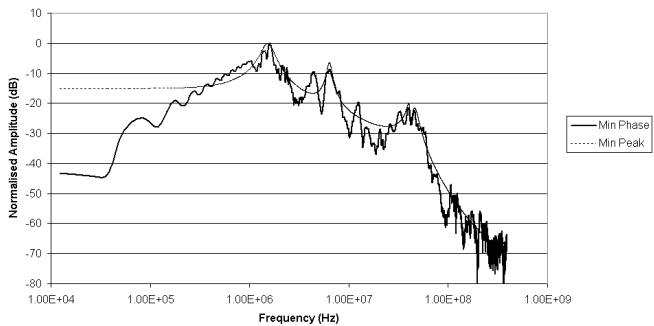


Fig. 11. Minimum Phase Result Compared with Minimum Peak Result – IEC 61000-2-9 Early-time EMP. This graph enables a comparison in the frequency domain between the results of the traditional minimum phase algorithm and the new minimum peak algorithm. The fit of the modeled transfer function when convolved with the threat waveform compares well to that of the minimum phase result.

Minimum Peak Result Compared with Minimum Phase Result
20MHz Damped Sinusoid

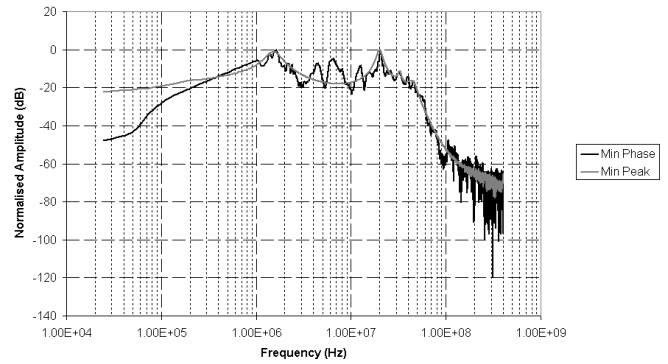


Fig. 12. Minimum Phase Result Compared with Minimum Peak Result – 20MHz Damped Sinusoid. This graph enables a comparison in the frequency domain between the results of the traditional minimum phase algorithm and the new minimum peak algorithm. The fit of the modeled transfer function when convolved with the threat waveform compares well to that of the minimum phase result.

The peak values for both techniques are as follows:

IEC HEMP E1 waveform:

Minimum Phase = 9.7A

Minimum Peak = 6.9A

20MHz Damped Sinusoid waveform:

Minimum Phase = 0.9A

Minimum Peak = 0.6A

For these examples, the difference for both waveforms is approximately 3dB. Fig. 13 and Fig. 14 show the minimum peak and minimum phase results in the frequency domain. As can be seen, good agreement between the minimum phase and minimum peak results has been achieved demonstrating that the general shape of the original transfer function has been modeled well by the Steiglitz-McBride method at the main resonant frequencies of interest.

B. Validation

The algorithm has been applied to a set of approximately 500 transfer functions measured for various cable bundles distributed over the same aircraft. Three different HPEM environments have been used:

1. In-band Damped Sinusoidal waveform (20MHz)
2. Out-of band Damped Sinusoidal waveform (50MHz)
3. HEMP waveform defined in IEC 61000-2-9

The largest ratio between the minimum peak and the minimum phase predictions have been taken for each transfer function using the algorithm with parameter sets of 8 poles, 10 zeros and 10 poles, 12 zeros. Fig. 15, Fig. 16 and Fig. 17 present histograms of the various cases. The statistical summary given in Table 1 demonstrates that the minimum peak method gives peaks which, on average, are significantly lower than the minimum phase method.

Comparison of Minimum peak to Minimum Phase Predictions
20 MHz Damped Sinusoid

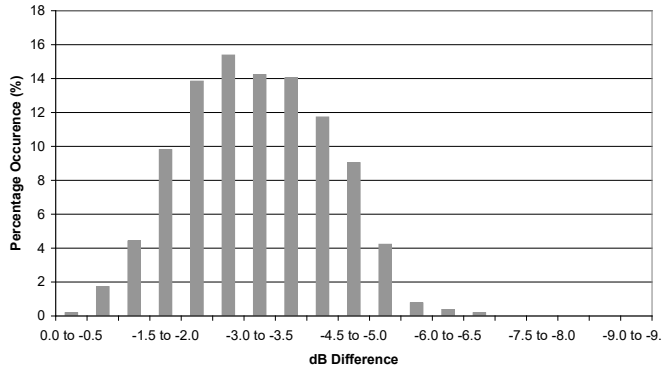


Fig. 13. Comparison of Minimum Peak with Minimum Phase Predictions – 20 MHz Damped Sinusoid. This graph shows the difference between the minimum peak and minimum phase predictions when using a 20MHz Damped Sinusoidal HPEM environment.

Comparison of Minimum Peak to Minimum Phase Predictions
60MHz Damped Sinusoid

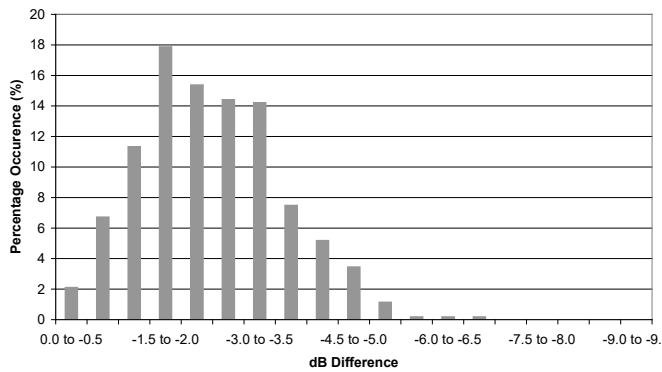


Fig. 14. Comparison of Minimum Peak with Minimum Phase Predictions – 50 MHz Damped Sinusoid. This graph shows the difference between the minimum peak and minimum phase predictions when using a 20MHz Damped Sinusoidal HPEM environment.

Comparison of Minimum Peak to Minimum Phase Predictions
HEMP IEC 61000-2-9

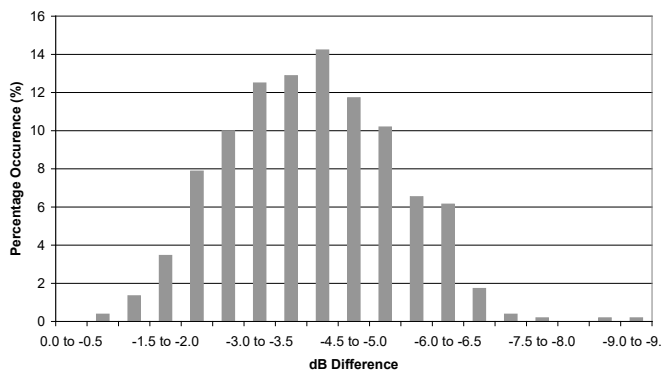


Fig. 15. Comparison of Minimum Peak with Minimum Phase Predictions – IEC 61000-2-9. This graph shows the difference between the minimum peak and minimum phase predictions when using the HEMP environment specified in IEC 61000-2-9.

V. CONCLUSION

A new method for predicting induced current as a result of

TABLE I
SUMMARY OF MINIMUM PEAK RESULTS

Environment	Mean (dB)	Standard Deviation (dB)
20MHz DS	-3.2	1.1
60MHz DS	-2.5	1.1
HEMP	-4.1	1.3

Mean and standard deviation of the minimum peak and minimum phase differences.

excitation of a system by an incident HPEM environment is presented. This technique has been shown to be useful in computing a lower bound to accompany the traditional MPA predictions. It can similarly be used to assess loom-by-loom variation due to the MPA prediction. In order to ensure accuracy in the results, care must be taken with respect to the modeling of the original transfer function. The Steiglitz-McBride method provides this initial good fit.

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Mr. Wraight joined the QinetiQ Electromagnetic and Environmental Services group (previously the Defence Evaluation and Research Agency, DERA), Farnborough, Hampshire, UK in January 2000 and is currently Technical Leader – Project Support. His primary role concerns the assessment and protection of systems against Electromagnetic Environmental Effects (E³) and has presented at several conferences internationally. His current research interests include the improvement of methodologies for the assessment of system level vulnerability.

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John Robinson (M '89) is a Member of the Signal Processing Society and the EMC Society. Mr. Robinson received the M.S. in Electrical Engineering from USC with emphasis on Signal and Image Processing in 1992, and the B.A. in Physics from UC San Diego in 1979. He has 15 years experience in the field of EMP signal processing, including dealing with issues of

sensors and simulators, test methodologies, data compression, stress prediction, uncertainty analysis, and scientific database products. From 1984-1993 he worked at TRW, he participated in five aircraft EMP assessments. From 1993 to the present he has been employed by Scientific Applications & Research Associates (SARA), Inc. in Cypress, California, where he is currently the venture team leader for database products integrated with specialized MATLAB toolboxes for EM, acoustic, and seismic field tests. Mr. Robinson holds numerous awards, including a NASA Certificate of Recognition for Creative Development of Technically Significant Software entitled "Thunderstorm Localization Using MUSIC and Associated Software" October 1998; the Meritorious Paper Award, "EMP Hardness Surveillance Test Technique Based on Ambient Man-Made Radiators" for the Hardened Electronics and Radiation Technology Conference in Monterey, California, March 1999; and he also is co-inventor on US Patent No US 6,526,365 B1 "Low-power Wideband Transfer Function Measurement Method and Apparatus", Awarded Feb. 25, 2003.



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Mr Marson initially worked on software for data capture for aircraft EMC trials and was heavily involved with the development of the QinetiQ Dream database with SARA Inc.

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