PAPER • OPEN ACCESS

Diagnostics of the printed circuit board bus of a spacecraft autonomous navigation system with using the *N*-norms

View the article online for updates and enhancements.

Diagnostics of the printed circuit board bus of a spacecraft autonomous navigation system with using the *N*-norms

R R Gazizov[1], B S Muhambetzhanova[1], T T Gazizov[2] and A A Kvasnikov[1]

[1]Department of Television and Control, Tomsk State University of Control Systems and Radioelectronics, 40, Lenin Ave., Tomsk, 634050, Russian Federation
[2]Department of Information Systems Development and Electronic Document Management, Tomsk State Pedagogical University, 60, Kievskaya Str., Tomsk, 634061, Russian Federation

E-mail: ruslangazizow@gmail.com

Abstract. The paper presents the study of the printed circuit board bus of the autonomous navigation system of a spacecraft using the amplitude criteria based on *N*-norms. During the study, the authors revealed the most vulnerable places on the bus by calculating the five *N*-norm profiles along the active conductor of the bus (in 280 segments). The results showed that the peak voltage was reduced by 6.2 % to the end of the active conductor, the signal rate changed sharply but insignificantly (within ±9.3 %) along the active conductor and reduced (by 20 %) towards its end. However, the energy characteristics of the excitation along the active conductor changed insignificantly.

1. Introduction

Nowadays, the radioelectronic equipment (REE) is developing at a fast pace, package density of its internal structures is increasing, as well as the frequencies of useful and interfering signals. It makes the requirements for providing electromagnetic compatibility (EMC) more stringent. With increasing the complexity of REE, the probability of electromagnetic interference increases which adversely affects its performance. This is especially dangerous in critical systems, for example, in the space industry. Therefore, the diagnostics of the developed REE is becoming critical to avoid possible faults and failures. This is especially important for printed circuit boards (PCB) because their conductors in general are placed arbitrarily. A special place in such diagnostics is occupied by simulation modeling since it allows us to obtain sufficiently correct information about REE with minimal effort and without carrying out a full-scale experiment.

One of the criteria for such diagnostics can be the amplitude criteria based on the *N*-norms that C. Baum proposed in 1979 [1]. To calculate them, you need to know the signal waveform in the time domain. Earlier, in Tomsk State University of Control Systems and Radioelectronics (TUSUR) a computer simulation software TALGAT was developed which was specifically dedicated to solving EMC problems [2]. The TALGAT software provides the possibility to calculate signal waveforms along the conductors of an arbitrary circuit of multi-conductor transmission lines (MCTL) on the basis of the theory from [3–5]. In addition, the ability to calculate *N*-norms based on the obtained waveform has been recently added to the system. With the help of the implemented functionality, a number of investigations were carried out: in the test circuits of single and coupled transmission lines, as well as the meander lines with one and two turns. However, more complex circuits have not been investigated.

Meanwhile, this can be done by the example of a PCB bus of an autonomous navigation system (ANS) of a spacecraft, developed in TUSUR within the design and development work on "SAN". One of the important tasks is to diagnose the signal bus of the PCB for possible failures. Therefore, the purpose of this work is to study the spacecraft ANS PCB bus with the help of the *N*-norms.

2. Theoretical Bases

2.1. The structure under the investigation

As a structure under the investigation, we took the ANS PCB bus. The PCB fragment and its circuit diagram are shown in figures 1 and 2, respectively. The resistances at the ends of each conductor were assumed to be 50 Ω. A conductor bend and a via were approximately simulated as the parallel capacitance of 1 pF and series inductance of 1 nH, respectively. The cross sections of each MCTL section were simulated and per-unit-length matrices **L** and **C** were calculated according to PCB stack parameters. Each MCTL section was numbered. The trapezoidal ultrashort pulse with electromotive force amplitude of 1 V was used as excitation. The whole duration was 3 ns and it was proposed that this ultrashort pulse was a wanted signal.
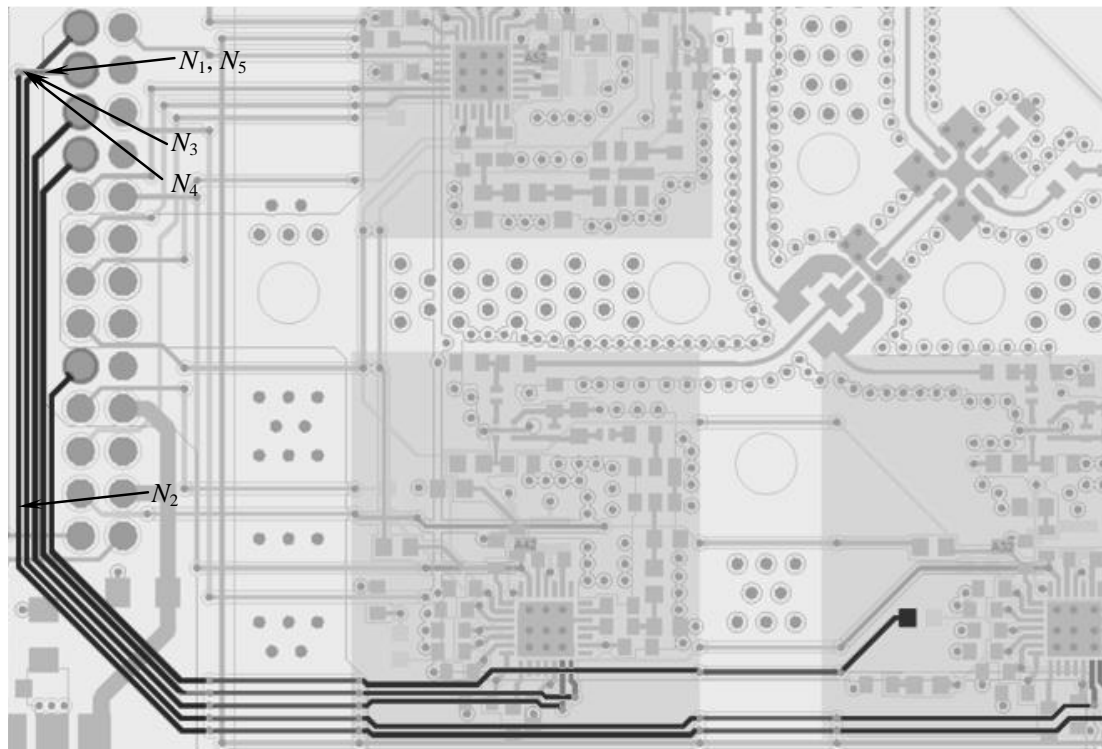

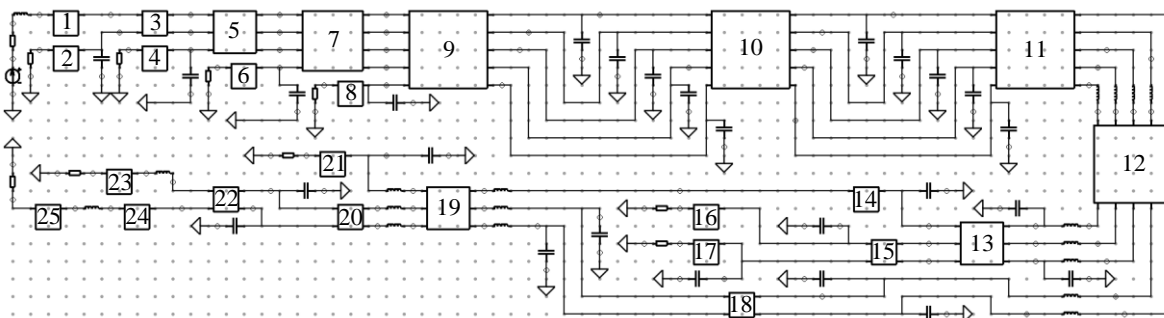**Figure 1.** The PCB fragment with the bus under the investigation.

Figure 2. The PCB bus circuit diagram.

2.2. Signal waveforms calculation

The theoretical bases and algorithms to calculate the quasistatic response along each conductor of each MCTL section connected to the multiconductor network were developed earlier and presented in [5]. But it seems to be important to present them again to clarify the method.

Frequency domain equations are used to calculate voltage and current responses in the MCTL section:

$$\mathbf{V}(x) = \mathbf{S}_V\,(\mathbf{E}(x)\mathbf{C1} + \mathbf{E}(x)^{-1}\mathbf{C2})\,, \tag{1}$$

$$\mathbf{I}(x) = \mathbf{S}_I\,(\mathbf{E}(x)\mathbf{C1} - \mathbf{E}(x)^{-1}\mathbf{C2}) \tag{2}$$

where $\mathbf{S}_V$ and $\mathbf{S}_I$ are the matrices of modal voltages and currents; $\mathbf{E}(x)$ is the diagonal matrix {exp($-\gamma_1 x$), exp($-\gamma_2 x$), …, exp($-\gamma_{N_k} x$)} and γ_{N_k} is the propagation constant for the *k*-th MCTL section, N_k is a number of conductors in the *k*-th MCTL section, x is the coordinate along the MCTL section. The calculation of $\mathbf{S}_V$, $\mathbf{S}_I$, and $\mathbf{E}(x)$ is described in [4]. **C1**, **C2** are constant vectors calculated as:

$$\begin{bmatrix} \mathbf{C1} \\ \mathbf{C2} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_V & \mathbf{S}_V \\ \mathbf{S}_V\mathbf{E}(l) & \mathbf{S}_V[\mathbf{E}(l)]^{-1} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{V}(0) \\ \mathbf{V}(l) \end{bmatrix} \tag{3}$$

where $\mathbf{E}(l)=\mathbf{E}(x)$ for $x=l$; l is the length of the MCTL section; $\mathbf{V}(0)$ and $\mathbf{V}(l)$ are vectors describing the voltage at the ends of the MCTL section, determined after solving the equation for the circuit with n MCTL sections with lumped elements at the ends:

$$\mathbf{V}(s) = \left(s\mathbf{W} + \mathbf{H} + \sum_{k=1}^{n}\mathbf{D}_k\mathbf{Y}(s)_k\mathbf{D}_k^t \right)^{-1}\mathbf{E}(s) \tag{4}$$

where $s = j\omega$, ω is angular frequency; **W**, **H** are matrices of order $A{\times}A$ describing the lumped memory and memoryless elements of network, respectively (A is the number of parameters, which are calculated by the modified node potential method); $\mathbf{D}_k=[i, j]$ with entries $l_{i,j}\in\{0, 1\}$, where $i\in\{1, …, N_k\}$, $j\in\{1, …, 2N_k\}$ with one nonzero value in each column, is the selector matrix that maps the terminal currents of the *k*-th MCTL section; $\mathbf{Y}(s)_k$ is the conductance matrix of the *k*-th MCTL section; $\mathbf{V}(s)$ is the vector of node voltage waveforms; $\mathbf{E}(s)$ is a constant vector with entries determined by the independent voltage and current sources.

The algorithm used to calculate the response is described in [5]. First of all, the initial time domain excitation is transformed into the frequency domain by means of the forward fast Fourier transformation (FFT). Then calculations of (1)–(4) are carried out. The obtained result is transformed into the time domain by means of inverse FFT.

2.3. N-norm calculation

A summary of the definitions of the N_1–N_5 norms is presented in table 1, reproduced from [1, 6]. *N*-norms are parameters which are used to characterize a signal in the time domain and historically have been proposed to determine the limits of equipment susceptibility. The particular interest to the use of the norms is explained by the fact that they can be used to indicate the effect of the given field on systems [1, 7]. The *N*-norms calculation is based on the application of the mathematical operators to the entire signal waveform.

3. Simulation results

Each MCTL section was divided into 20 segments, in each of which the signal waveforms were calculated. First, we calculated the waveforms along the active conductor, and then we calculated the values of the *N*-norms in each segment of all MCTL sections along this conductor (Figure 3).

Let us consider the graph showing how the N_1 value changes (Figure 3). As can be seen from table 1, the N_1 norm shows the maximum signal value, therefore, the largest value of this norm (0.532 V) is observed at the beginning of the conductor. Then, as the number of segments increases, the value decreases almost evenly to 0.5 V (by 6.2 %) when the segment reaches 200. This segment is located at the end of the MCTL section 19 (Figure 2).
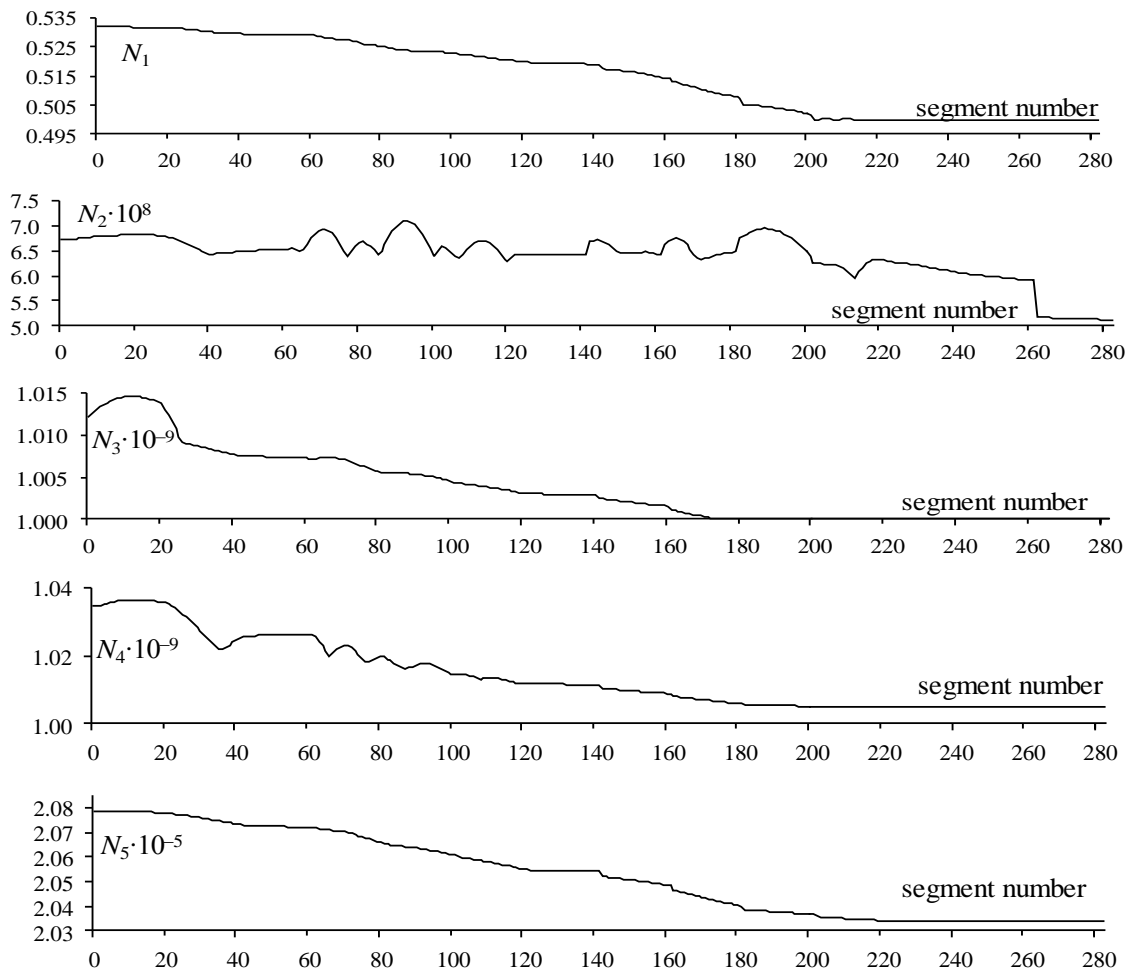
Figure 3. The graphs of changes in the *N*-norm values along the active conductor.

Table 1. *N*-norm parameters, description, and application.

N-norm	Name	Application
$N_1 = \left| R(t) \right|_{max}$	The peak (absolute) value	Scheme fault / electric breakdown / electric arc effects
$N_2 = \left| \dfrac{\partial R(t)}{\partial t} \right|_{max}$	The peak (absolute) derivative	Component sparkling / scheme fault
$N_3 = \left| \displaystyle\int_0^t R(t)dt \right|_{max}$	The peak (absolute) pulse	Dielectric breakdown (if R means the E field)
$N_4 = \displaystyle\int_0^t \left| R(t) \right| dt$	Rectified general pulse	Equipment damage
$N_5 = \left\{ \displaystyle\int_0^\infty \left| R(t) \right|^2 dt \right\}^{\frac{1}{2}}$	The square root of the action integral	Component burning-out

Let us consider a graph illustrating the changes in the N_2 value, which characterizes the rate of the signal change. Up to segment 200, we can observe sharp, but insignificant (within ±9.3 %) changes in the N_2 values. After segment 200, there is a sharp decrease in the N_2 value by 20 %. There are 4 local maximums: in segments 25 (MCTL section 3), 69 (MCTL section 7), 94 (MCTL section 9), 191 (MCTL section 19), having the values of about $7 \cdot 10^8$. This means that the probability of sparking in these segments is the greatest. Let us consider the graph of changes in the N_3 value. The value of the norm decreases, but only by 1.4 %. Consequently, under this excitation, the probability of dielectric breakdown along the active conductor in this bus does not change. The values of N_4 and N_5 norms also change insignificantly. So the probabilities of equipment damage and component burning-out hardly change along the line.

4. Conclusion
In this study, the spacecraft ANS PCB bus has been investigated for possible vulnerabilities using N-norms. Five N-norms have been calculated in each segment of each MCTL section along the active conductor (280 segments in total). The used approach allows us to reveal the places where the highest values of the norms are localized. The considered example showed a decrease in the peak voltage at the end of the active conductor by 6.2 % and revealed local increases of signal change rate along the active conductor and decay to its end. However, energy excitation characteristics along the active conductor change insignificantly.

5. Acknowledgments

References
[1] Baum C 1979 Norms and Eigenvector Norms *Mathematics Notes* Note **63** 1–42
[2] Kuksenko S P, Gazizov T R, Zabolotsky A M, Ahunov R R, Surovtsev R S, Salov V K and Lezhnin Eg V 2015 New developments for improved simulation of interconnects based on method of moments. Advances in Intelligent Systems Research *Proc. of the 2015 Int. Conf. on Modelling, Simulation and Applied Mathematics (MSAM2015)* pp 293–301
[3] Djordjevic A R and Sarkar T K 1987 Analysis of time response of lossy multiconductor transmission line networks *IEEE Trans. Microw. Theory Tech.* **35(10)** 898–907
[4] Zabolotsky A M 2016 *Models, Algorithms, Methods, Technologies and Devices for Electromagnetic Compatibility Providing of an Onboard Spacecraft Radioelectronic Equipment* Doctoral dissertation, Tomsk State University of Control Systems and Radioelectronics
[5] Gazizov R R 2018 *Mathematic Model, Numerical Method, and Software Complex for Revealing and Localization of Signal Extremes in Multiconductor Transmission Lines,* PhD dissertation, Tomsk State University of Control Systems and Radioelectronics
[6] Giri D 2004 High-Power Electromagnetic Radiators: Nonlethal Weapons and Other Applications (Cambridge, MA: Harvard University Press)
[7] *IEC "61000-4-33 2005 Electromagnetic compatibility (EMC) – Part 4-33: Testing and measurement techniques – Measurement methods for highpower transient parameters"* ed: IEC