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Methods for increasing noise immunity of radio electronic systems with redundancy

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Methods for increasing noise immunity of radio electronic systems with redundancy

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Abstract. The idea of increasing the noise immunity of radioelectronic systems with redundancy is presented. Specific technical solutions based on this idea of modal redundancy are described. An estimation of noise immunity improvement was performed by the example of implementation of modal redundancy with the broad-side electromagnetic coupling for a printed circuit board of the digital signal processing unit for an autonomous navigation system of a spacecraft. It is shown that the implementation of modal redundancy can provide an attenuation coefficient for the interference signal up to 12 dB.

1. Introduction

The implementation of the achievements of science and modern technologies is characterized by the creation of complex systems and devices with a high level of automation, performing intelligent, adaptive control functions in space and aviation technology, thermal and nuclear power engineering, chemical, petrochemical, oil and gas, metallurgy, processing and other fields of industries and transport. Successful solution of the management tasks related to increasing the efficiency of the production facilities posed the problem of ensuring high reliability of such systems and technical means as a priority. The importance of this problem is due to the possible significant damage that can occur in hazardous industries and industries with large unit capacities [1].

Redundancy is practically the only and widely used method for principally improving the reliability of automation systems. It allows one to create alarm systems, emergency protection, automatic fire extinguishing, monitoring and management of explosive technological units and others related to safety levels SIL1–SIL3 in accordance with IEC 61508-5 [2], as well as critical systems in which even a short hold leads to large financial losses (electricity distribution systems, management of continuous technological processes, tracking of moving objects, etc.). Redundancy allows the creation of highly reliable systems made of typical devices [3], using a similar, inactive part of the electronic equipment in the event of a malfunction in the functioning part.

In addition, at present time, there is a growing threat of deliberate electromagnetic interference to electronics [4]. Such impact can lead to breakdown or malfunction of electronic equipment. In particular, the impact of ultrashort pulses (USP) is especially dangerous, because existing network filters do not protect against them [5]. There are only a few industrial devices that protect against USP, but they have large dimensions and high cost. Thus, at present there is no inexpensive and effective protection against ultra-wideband pulses. Nevertheless, the growing role of electronics makes this protection more and more relevant. The need for proper protection against USP significantly complicates all parts and, as a consequence, the final design of the systems. Meanwhile, the presence of redundancy allows us to look for ways to use it rationally.

Using the excessiveness of redundancy and modal filtering, an idea modal redundancy (MR) is proposed which allows improving the protection of electronics against electromagnetic interference. This idea [6] of redundant electrical connections is distinguished by the consideration of electromagnetic coupling between the reserved (active) and the reserving (passive) conductors of the reserved and reserving circuits. The result is a decrease in the susceptibility of the reserved circuit to external conductive emissions and a decrease in the level of conductive emissions from the reserved circuit. In the event of failure of the reserved circuit, a similar result will be achieved in the reserving circuit. It is achieved due to the fact that an interference signal (whose duration is less than the difference in the even and odd mode delays in a structure of a coupled line formed by a pair of the reserved and reserving circuit conductors) undergoes modal distortions: decomposition into smaller pulses (when considering a signal in the time domain). The idea of modal reservation is realized in a number of patents for invention [7-9], whose materials are also presented in international journals and conferences. However, they contain only specific technical solutions for increasing the noise immunity of circuits with redundancy.

The purpose of this work is a systematic description and representative demonstration of the new ways to improve the noise immunity of radioelectronic systems with redundancy. In Section 2, a short description of the idea of modal reservation is made with an assessment of the advantages and disadvantages of various options for its implementation. Section 3 presents the results of a quasistatic simulation of electrical connections with MR, proving the possibility of achieving the technical result. Section 4 shows an example of the realization of MR in the circuits of digital signal processing unit for autonomous navigation system of a spacecraft. Section 5 presents a conclusion of the work.

2. Modal redundancy

The simplest way to implement the MR is to use an edge coupled line (Figure 1a) [7], where the reserved (active) and reserving (passive) conductors have the same reference conductor, the reserved and reserving conductors of the corresponding circuits are paired, parallel to each other, on one layer with a minimally technologically permissible gap between them. Another way is to place the corresponding components on opposite sides of the reserved and reserving printed circuit boards (PCB) [8]. This arrangement allows for implementation of face coupling between the reserved and reserving traces, with the reference conductor being in form of two polygons (Figure 1b). A distinctive feature of the third way (Figure 1c) is the fact that the top and bottom layers of the double-sided PCB are filled with polygons that are the reference layers for the reserved and reserving traces [9].

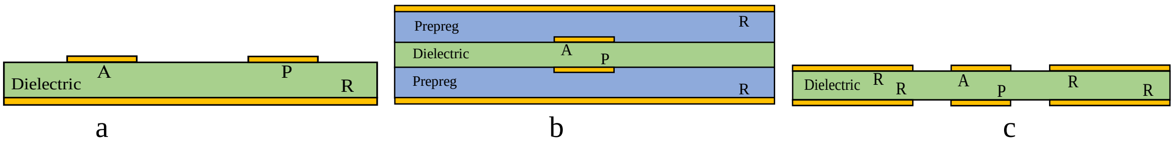

Figure 1. A cross-section of a structure: a – with edge coupling; b – with broad-side coupling; c – with gaps in reference planes: A – active, P – passive, R – reference.

Each way of layout has its own field of application. For example, the MR with the edge electromagnetic coupling can be used for a single-sided PCB. The MR with the broad-side electromagnetic coupling is relevant a of multi-layer PCB. At the same time, MR with gaps in the reference plane is appropriate for double- and single-sided PCBs. It is worth noting that each of the ways has its advantages and disadvantages, which are described below.

For structures with the edge electromagnetic coupling, the advantage is the absence of the need for a complex technological process of PCB manufacturing. The disadvantage is that the control of the delay difference of the modes can be performed with a relatively small set of parameters (the length of the interconnects, the relative permittivity of the substrate). In view of the edge electromagnetic coupling, the attenuation coefficient is not much more than 6 dB per section with the total decomposition of an interference pulse. The implementation is convenient only with components where the reserved and reserving parts are made in one package, and the package leads are symmetrical or pairwise. Otherwise, there are problems with a tracing.

For structures with the broad-side coupling, the advantage lies in the fact that the implementation of this method does not require complex technological processes and re-tracing of PCB, since the reserved and reserving traces are performed on separate inner layers of the multi-layer PCB. There are no restrictions on the element base. Ground and power planes serve as shields for interconnections located on inner layers. The disadvantage is the arrangement of the elements to each other, which can negatively influence reliability, since both (reserved and reserving) components will be subjected to any negative influence (for example, temperature or vibration). The implementation of the method requires the mounting the components on both sides of the PCB.

For a structure with gaps in the reference planes, the advantage is the increase in degrees of freedom in the design of the PCB. The disadvantage is the violation of the integrity of the reference planes. Implementation requires an excessive area (free of traces and components).

3. Quasistatic analysis of electrical connections

To illustrate the possibility of achieving the technical result claimed in the patents [7–9], quasistatic simulation for each of the three structures is performed in TALGAT software. It is based on the method of moments and allows one to make 2D quasistatic analysis of arbitrary complexity structures. The algorithm implemented in the software allows calculating matrices of the line parameters **L**, **C**, **Z** and mode delays. Using the modified node-potentials method in the frequency domain, it is possible to calculate the time response through a fast Fourier transform.

The circuit from Figure 2 was used for simulation of voltage waveforms for three structures (Figure 1) with length of 1 m. Loads at the ends of the line are 50 Ohm resistors. Impulse interference with EMF of 2 V and rise, flat top and fall times of 100 ps was excited between the active (reserved) and the reference conductors. Waveforms at the near (*V*1) and the far (*V*3) ends of the reserved (active) conductor for three structures are shown in Figure 3.

For the structure with the edge electromagnetic coupling (Figure 1a), two decomposition pulses with amplitudes of 0.5 V (Figure 3a) are shown, which is half the level of the impulse noise (1 V) at the near end of the line. For the structure with the broad-side electromagnetic coupling (Figure 1b), two decomposition pulses with amplitudes of 0.4 V (Figure 3b) are shown, which is 2.5 times smaller than the impulse noise level (1 V) at the near end of the line. For the structure with gaps in the reference plane (Figure 1c), three decomposition pulses with maximum value of amplitudes of 0.5 V (Figure 3c) are shown, which is 1.6 times lower than the impulse noise level (0.8 V) at the near end of the line. The decomposition of impulse noise into pulses of a smaller amplitude ensures a decrease in the susceptibility of the redundant circuits to external conductive emissions.

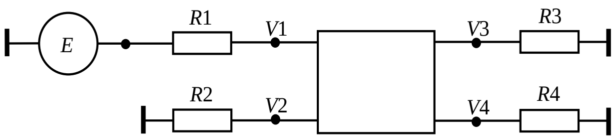

Figure 2. A circuit diagram of the simulated structure.

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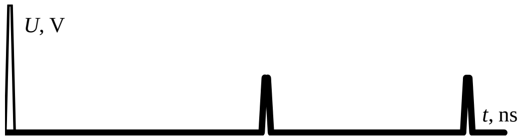
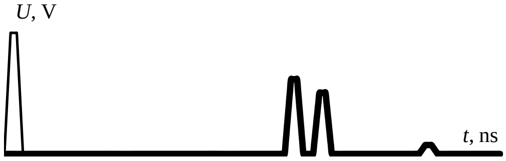
a



b



c

Figure 3. Simulated waveforms at near (–) and far (**—**) ends of reserved conductors: a – with edge coupling; b – with broad-side coupling; c – with gaps in reference planes.

4. Quasistatic simulation of ultrashort pulse propagation in circuit with modal reservation

As the structure under study, the PCB of the digital signal processing unit [10] for the spacecraft (Tables I and II) autonomous navigation system was chosen in two implementations: without (Figure 4) and with (Figure 5) modal redundancy. The interference signal (with an EMF of 5 V and front, flat top and decay times of 100 ps) excites the circuit "A/B_DAC_A52".

To simulate the propagation of the interference signal, it is necessary to take into account the effects of interconnect density in a real PCB. Therefore, the PCB is broken up into fragments shown in Figures 4 and 5. For each cross-section of the fragments, the matrices of per-unit-length coefficients of electrostatic and electromagnetic induction are calculated in the TALGAT system. The calculated coefficients of matrices **C** and **L** are recorded in the corresponding circuit blocks (Figure 6). The value of the resistors is chosen to be 50 Ohm.

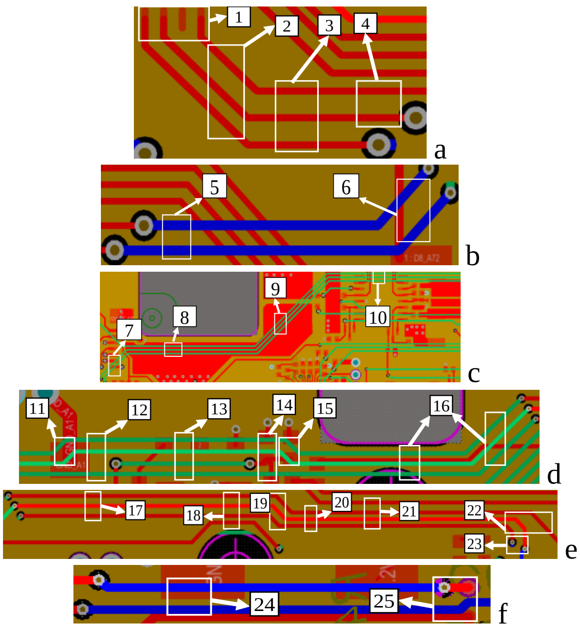


Figure 4. Fragments of PCB without modal reservation: a – 1–4; b – 5–6; c – 7–10; d – 11–16; e – 17–23; f – 24–25.

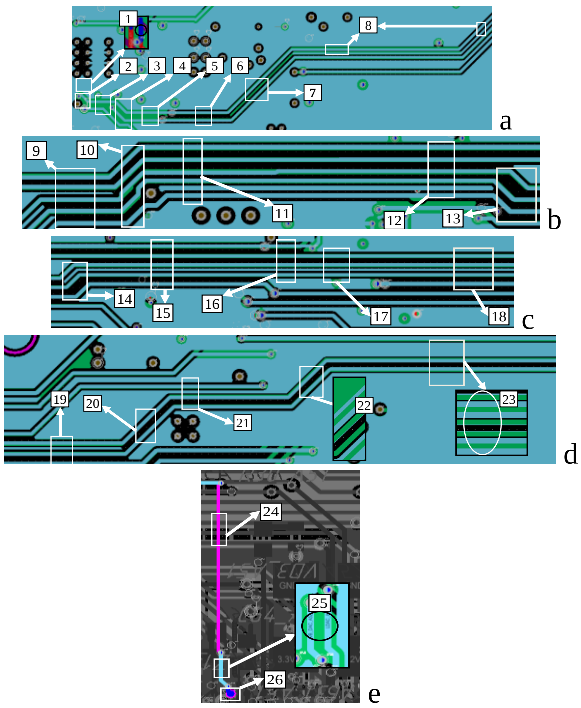


Figure 5. Fragments of PCB with modal reservation: a – 1–8; b – 9–3; c – 14–18; d – 19–23; e – 24–26.

Table 1. Cross-sections and sizes of fragments of the PCB without modal reservation

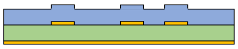
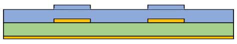
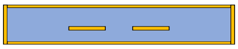
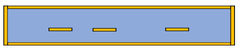
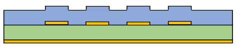
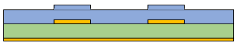
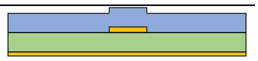
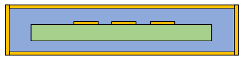
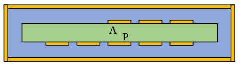
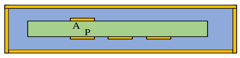
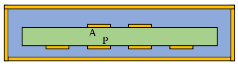
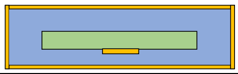
№	Sizes, *mm*			Cross-sections
	l	*w*	*s*1 / *s*2 / *s*3	
1	0.5	0.2	0.8 0.4 -	
6	2.48	0.3	0.761 - -	
7	8.18	0.3	0.407 - -	
12	2.88	0.3	0.575 1.325 -	
18	3.5	0.3	0.45 0.45 0.2	
25	0.75	0.3	0.7 - -	

Table 2. Cross-sections and sizes of fragments of the PCB with modal reservation

№	Sizes, *mm*			Cross-sections
	l	*w*	*s*	
1	1	0.254	-	
4	2.28	0.254	0.424	
9	28.17	0.254	0.4	
14	1.41	0.254	0.4	
22	3.89	0.254	0.4	
24	12.02	0.254	-	

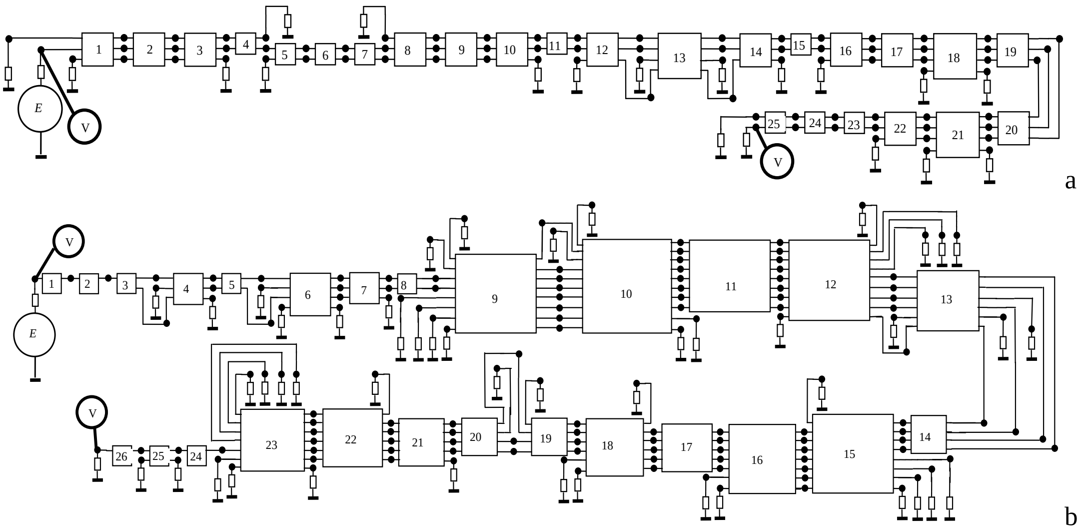


Figure 6. A schematic diagram of the circuit for simulating the propagation of a pulse signal in fragments of PCB: a – without; b – with modal reservation.

Simulated voltage waveforms at the input and output of the circuit without modal reservation (Figure 6a) are presented in Figure 7a. The amplitude of the pulse was slightly attenuated by 3 dB. Results for the circuit with modal reservation (Figure 6b) are presented in Figure 7b. In this case ε_{r2} = 4.2, and the amplitude of the interference impulse was attenuated by 8 dB. Then we changed the ε_{r2} from 4.2 to 10, and new **C** and **L** matrices were written into circuit blocks of Figure 6b. Simulated waveforms are shown in Figure 7c. The amplitude of the pulse was attenuated by 11.9 dB.

Comparison of output waveforms is shown in Figure 7d. It is seen that the amplitude of the output signal with modal redundancy can be considerably attenuated even in high density interconnects environment.

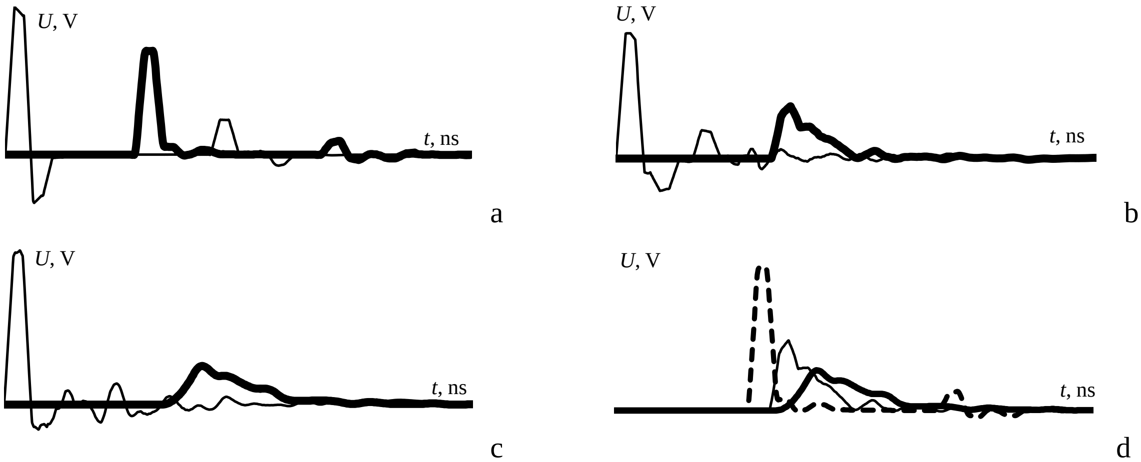


Figure 7. Voltage waveforms at near and far ends of the line for PCB: a – without modal reservation; b – with modal reservation when $\varepsilon_r = 4.2$; c – with modal reservation when $\varepsilon_r = 10$. Comparison of waveforms (d) at the far end without modal reservation (- -) and with modal reservation when $\varepsilon_{r2} = 4.2$ (–) and $\varepsilon_{r2} = 10$ (**–**).

5. Conclusion

In this paper, methods of arranging and tracing PCBs for redundant circuits are described. Modal redundancy with the edge coupling, with the broad-side coupling and with gaps in the reference plane are considered. Let us note that with the implementation of modal redundancy with the broad-side coupling, the technical process becomes more complicated; however, it is possible to achieve a higher attenuation coefficient with respect to other ways.

An estimation of noise immunity improvement was performed by the example of implementation of modal redundancy with the broad-side coupling for a PCB of the digital signal processing unit for an autonomous navigation system of a spacecraft. The attenuation coefficient of the circuit without modal redundancy is 3 dB. Implementing modal redundancy only by changing the topology of the printed circuit board increases the attenuation coefficient up to 8 dB. The implementation of modal redundancy with a change in the permittivity of the layer between the active and passive traces increases the attenuation coefficient up to 12 dB.

The approaches of increasing the noise immunity of systems with redundancy described in this paper do not completely cover the possibilities of implementing modal redundancy. However, they are promising, and therefore further studies of modal redundancy are needed.

6. Acknowledgments

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