UDC 621.372.8.01

Siberian Journal of Science and Technology. 2018, Vol. 19, No. 1, P. 44–48

MODAL FILTER SIMULATION WITH LOSSES

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Protection of spacecraft on-board equipment against electromagnetic interferences is an actual problem. Much attention is paid to the susceptibility to the excitation of powerful ultra short impulses (nanosecond and subnanosecond impulses). The use of known protection devices to solve this problem is hampered by a number of conflicting requirements. For example, low mass, high reliability, long life. In addition, ultrashort pulses are able to penetrate into various radio-electronic equipment by passing the instrument shields. Protection potential using the devices based on modal filtering is well known. To simulate these devices, rigorous electro-dynamic approach is applied, which requires high computational costs. Approximate quasi-static approach allows to significantly reduce computational costs. The quasi-static simulation was used in this paper, loss record in conductors was realized by means of exact calculation of the matrix of per-unit-length resistances through a change in the matrix of the per-unit-length coefficients of electromagnetic induction when scaling the cross section of conductors. The effect of losses on the shape and amplitude of the pulses at the output of the modal filter is shown. A comparison of simulation results with electrodynamic and quasi-static approaches taking into account losses is presented. Good consistency is obtained. Quasi-static simulation with losses took much less time than the electrodynamic simulation. Analysis of the results suggests that software-based approaches can be used for modal filter simulation.

Keywords: microstrip line, linear delay, wave impedance, modal filtering, quasi-static simulation, protection device.

Сибирский журнал науки и технологий. 2018. Т. 19, № 1. С. 44–48

МОДЕЛИРОВАНИЕ МОДАЛЬНОГО ФИЛЬТРА С УЧЕТОМ ПОТЕРЬ

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Защита бортовой аппаратуры космического аппарата от электромагнитных помех является актуальной проблемой. Большое внимание уделяется восприимчивости к воздействию мощных сверхкоротких импульсов (импульсов наносекундного и субнаносекундного диапазонов). Использование известных устройств защиты для решения данной задачи затруднено рядом противоречивых требований, например, малой массы, высокой надежности, длительного срока активного существования. Кроме того, сверхкороткие импульсы способны проникать в различную радиоэлектронную аппаратуру, минуя экраны приборов. Известна возможность защиты с помощью устройств, основанных на использовании модальной фильтрации. Для моделирования таких устройств применяют строгий электродинамический подход, который требует больших вычислительных затрат. Приближенный квазистатический подход позволяет значительно уменьшить вычислительные затраты. Использован учет потерь в проводниках при квазистатическом моделировании, реализованный с помощью точного вычисления матрицы погонных сопротивлений через изменение матрицы погонных коэффициентов электромагнитной индукции при масштабировании поперечного сечения проводников. Показано влияние потерь на форму и амплитуду импульсов на выходе модального фильтра. Представлено сравнение результатов моделирования электродинамическим и квазистатическим подходами с учетом потерь. Получена хорошая согласованность. Квазистатическое моделирование заняло значительно меньше времени, чем электродинамическое. Анализ результатов показал, что программно-реализованные подходы можно использовать для моделирования модального фильтра.

Ключевые слова: микрополосковая линия, погонная задержка, волновое сопротивление, модальная фильтрация, квазистатическое моделирование, устройство защиты.

Introduction. As long-term practice of start and maintenance of the spacecrafts (SC) showed, reliability of the elements, devices of airborne computers and control modules functioning is one of the key factors defining success of the mission in general. Reliability assurance in special conditions of harmful space factors impact is connected with specific difficulties. One of such factors is interfering super short impulse (ISI). Its dangers are extensively researched [1–5]. However, the increase in SC effective performance period (up to 15 years) leads to considerable degradation of the used materials' properties and also makes it problematic to predict the new materials' properties mutation in the future SCs. This will inevitably create conditions for harmful effects of ISI, causing improvements of protection against it. The use of the known protection devices is complicated by a number of contradictory requirements, for example, protection of a bigger number of circuits, law mass of the safety device, ability to function effectively for 15 years in space. Therefore creation of new elements and protection devices of airborne computers and control modules from SIS proves to be relevant. Protection against short impulses based on modal filtering [6–11] is suggested. The physical principle of such protection is based on the effect of splitting of interfering impulse in the segment of line into modes, each of which extends with the time delay. In case of unhomogeneous dielectric filling in the cross-section of the connected line segment, the difference of these time delays can exceed duration of interfering impulse, so that one impulse given between the active and reference conductors at the beginning of the segment will split into two impulses at the end of the segment.

Often for the analysis of strip structures quasi static simulation is used. For exact simulation of such structures it is necessary to consider losses both in conductors, and in dielectrics. Meanwhile, accurate loss record is especially important in certain cases. Thus, in modal filters (MF) output amplitude depends on losses.

The purpose of this paper is to compare results of quasi static and electro-dynamic simulations of MF taking into account loss record.

Calculation of resistance per-unit-length matrix. The algorithm of Calculation of resistance per unit length matrix of *N*-wire transmission line in which (N + 1) reference conductor, in quasi static simulation environment TALGAT [12] looks as follows [13]:

1. Input of conductor parameters: ρ – conductor specific resistance, μ – magnetic conductivity.
2. Input of frequency.
3. Input of the initial geometrical parameters.
4. Calculation of value of conductor boundaries extension ∂n (value 0.1 from the lowest parameter is used by default).
5. Calculation of the conductor's surface resistance using formula

$$R_s = \sqrt{\pi f \mu \rho}. \tag{1}$$

6. Geometrical modeling of cross-section structure under initial parameters.
7. Calculation of per-unit-length initial matrix coefficients of electromagnetic induction **L1**.
8. Extension of all boundaries of cross-section of the reference conductor on Δ*n*.
9. Calculation of inductance matrix **L2** for the changed structure.
10. Calculation of $\Delta\mathbf{L}_{j,k} = \mathbf{L2}_{j,k} - \mathbf{L1}_{j,k}$.
11. Calculation of non-diagonal matrix elements $\mathbf{R}_{jj}$ using formula:

$$\mathbf{R}_{j,k}\Big|_{j\neq k} = \frac{R_s}{\mu_0}\left(\frac{-\Delta\mathbf{L}_{j,k}}{\Delta n}\right), \text{ Om/m.} \tag{2}$$

12. Extension of all boundaries of the cross-section of the 1st from *N* conductors.
13. Calculation of $\mathbf{L2}_{jj}$.
14. Calculation of $\Delta\mathbf{L}_{jj} = \mathbf{L1}_{jj} - \mathbf{L2}_{jj}$.
15. Calculation of diagonal components of the matrix $\mathbf{R}_{jj}$ using formula:

$$\mathbf{R}_{jj} = \frac{R_s}{\mu_0}\left(\frac{-\Delta\mathbf{L}_{jj}}{\Delta n}\right), \text{ Om/m.} \tag{3}$$

16. Serial repetition of points 12–15 for each of the remained conductors, successively expanding boundaries of this conductor.

The calculation algorithm of matrix **R** has been implemented. In cases where it is required to calculate **L** matrix, functions of the TALGAT system are used. In the algorithm extension of conductor boundaries by value Δ*n* is applied. It is realized programmatically. The user value Δ*n* is set for this purpose, or default value Δ*n* equal to 0.1 from the lowest parameter of structure is used. For calculation of default value of boundary with the lowest length whose value is equated to value of the lowest parameter is found.

In order to expend the conductor *i*, where *i* = 1, 2, …, *N*, *N* – number of conductors multi-wire transmission line, applying scaling against the centre of the conductor, which transforms conductor coordinates $p_{1,i}$; $p_{2,i}$; …; $p_{M,i}$, where *M* – the number of conductor angles *i*, into coordinates $p_{1,i}'$; $p_{2,i}'$; …; $p_{N,i}'$ so to obtain the conductor, increased by Δ*n* from all sides. For this purpose scaling coefficients are calculated:

$$f_i^x = \frac{l_i^x + 2\Delta n}{l_i^x};\quad f_i^y = \frac{l_i^y + 2\Delta n}{l_i^y}, \tag{4}$$

where l_i^x, l_i^y – the width and thickness of conductor *i*. Further conductor center coordinates are calculated $p_{c,i}$ and transformation matrix is built:

$$\begin{matrix} f_i^x & 0 & 0 \\ 0 & f_i^y & 0, \\ p_{c,i}^x(1-f_i^x) & p_{c,i}^y(1-f_i^y) & 1 \end{matrix} \tag{5}$$

where $p_{c,i}^x$ and $p_{c,i}^y$ – components *x* and *y* coordinate $p_{c,i}$. Transformation matrix can be applied in the following way:

$$\begin{gathered} p_{j,i}^{x\,\prime} = f_i^x p_{j,i}^x + p_{c,i}^x\left(1-f_i^x\right); \\ p_{j,i}^{y\,\prime} = f_i^y p_{j,i}^y + p_{c,i}^y\left(1-f_i^y\right), \end{gathered} \tag{6}$$

where *j* = 1, 2, …, *M*. For the conductor boundaries extension transformation matrix should be applied (2) to every conductor angle. Extension of the infinite earth is done via displacement of all structure boundaries towards the line of the infinite earth on Δ*n*.

Simulation. The approaches described above are software realised and built-in in the TALGAT system. However, the use of this program for quasi-static simulation of real strip structures and comparing the received results with the results of electro-dynamic simulation was not shown earlier. For simulation MF structure, researched in [14], will be used.

Quasi-static simulation is executed in TALGAT system, electro-dynamic – in CST MWS [15]. The cross-section and the diagram of MF switch are provided in fig. 1, where width and thickness of conductors w = 500 micron and t = 85 micron; conductor spacing – s = 200, distance between edge of the conductor and dielectric edge d = 1000 micron, substrate thickness h = 400 micron, FR-4 substrate material, line length l = 2.5. MF contains three copper conductors: A – the active, O – reference and p – passive. The impulse oscillator is connected to the active conductor with the following parameters: amplitude – 10 V and duration of peak t_d = 100 picoseconds, duration of the front and recession of t_r = t_f = 100 picoseconds. Resistance values are R_1 = R_2 = R_3 = R_4 = = 100 Ohms. Results of simulation taking into account losses and dispersion are provided in fig. 2.

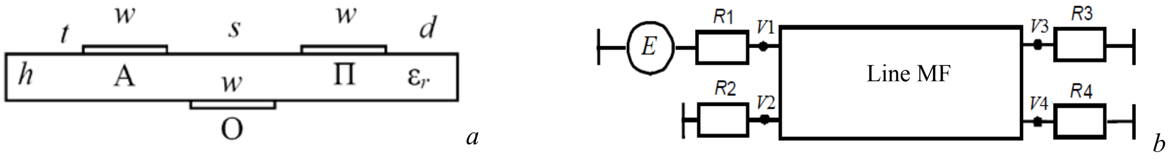

Fig. 1. MF cross-section (*a*) and connection scheme (*b*)

Рис. 1. Поперечное сечение (*a*) и схема включения (*b*) МФ

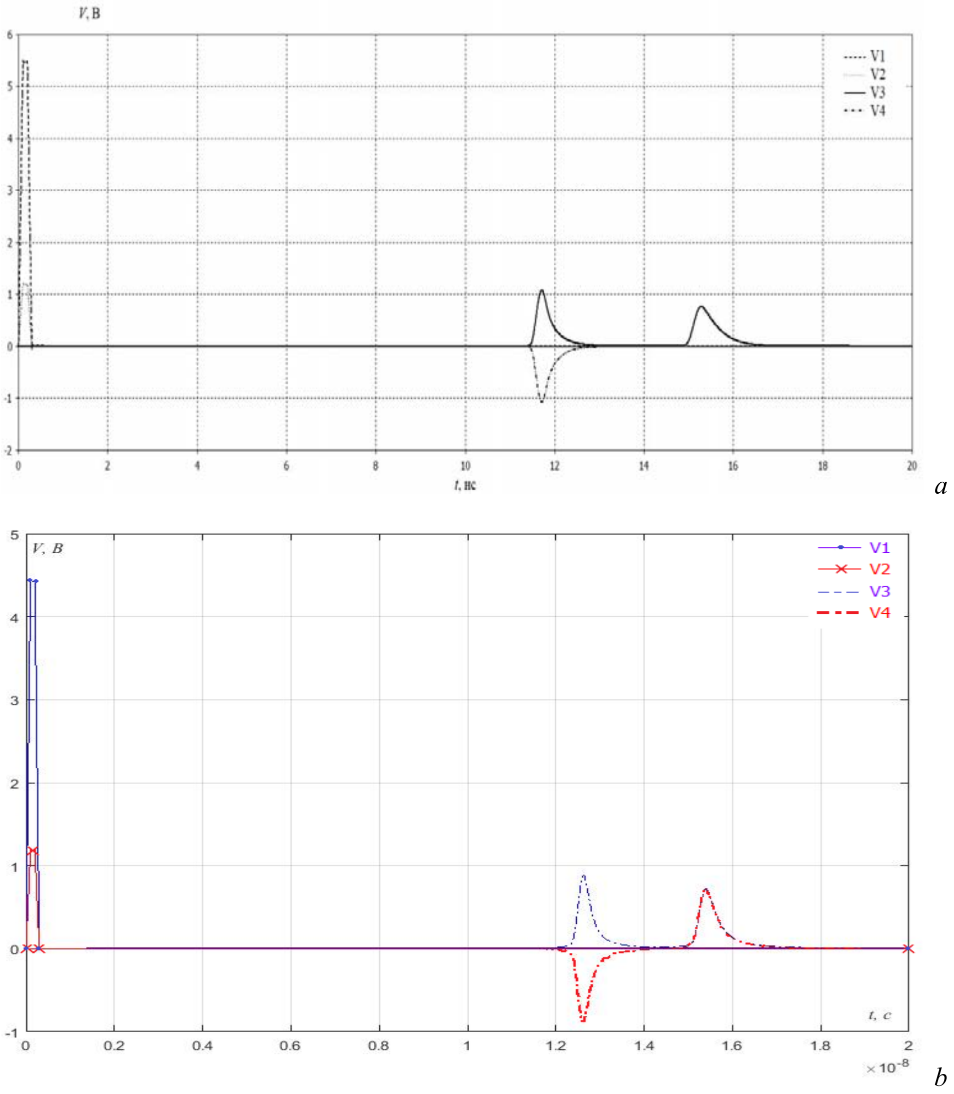

Fig. 2. Voltage waveforms obtained in CST MWS (*a*) and TALGAT (*b*)

Рис. 2. Формы напряжения, полученные в CST MWS (*а*) и TALGAT (*б*)

Table

Comparative results of amplitudes and impulses time delays

Parameter	CST	TALGAT	(CST – TALGAT)/(CST + TALGAT), %
Amplitude of 1st impulse *V*3, В	1.1	0.88	11
Amplitude of 2nd impulse *V*3, В	0.73	0.71	1.4
Amplitude of 1st impulse *V*4, В	–1.1	–0.88	11
Amplitude of 2nd impulse *V*3, В	0.73	0.71	1.4
Time delay of 1st impulse in nodes *V*3 and *V*4, ps	11.6	12.2	2.5
Time delay of 2nd impulse in nodes *V*3 и *V*4, ps	14.9	15	0.3

The results proved that with reference to losses in conductors and dielectrics, wavefront time and impulse drop on the MF output increase. Thus the voltage amplitude of output impulses (*V*3) is much less than a half of amplitude of an input impulse (*V*1). Impulse amplitude of the even mode appeared to be less than impulse amplitude of the odd mode. This results from the fact that currents of the even mode extend mostly in dielectric, while currents of the odd mode – in the air. Fig. 2 shows that voltage waveforms, calculated in TALGAT and CST MWS, coincide. Values of amplitudes and time delays of impulses are given in the table.

Conclusion. Simulation results showed that the maximum deviation under impulses delays makes 2.5 % under amplitudes – 11 %. It proves consistency of results received by means of the approaches described in the present paper. Besides. calculation time in TALGAT was about 1 h, in CST MWS – about 50 h. Therefore. the software realized approaches can be used for MF simulation**.**

Acknowledgments. This work was carried out as a result of the project 8.9562.2017/8.9 of the Ministry of Education and Science of the Russian Federation.

Благодарности. Работа выполнена за счет проекта 8.9562.2017/8.9 Минобрнауки Российской Федерации.

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