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Modeling of influences of sensor reflections on the accuracy of a microwave reflectometer

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Abstract

In this paper the uncertainty component of a multisensor microwave reflectometer dependent on mutual reflections between sensors is described. One-line and two-lines arrangement of the set of sensor localization are considered. Adjacent sensors influence each other. The mathematical model of signal flow graphs of such a system was developed. The set of linear algebraic equations incorporating main reflections between sensors was worked out. The least squares method or Kalman filter for averaging the sensor signals with random distortions is used. The uncertainty of measuring the power by the multi-sensor reflectometer is estimated. The obtained results are discussed. The described methods of the uncertainty evaluation can be applied to automation of the multi-sensor reflectometer and in other multivariable measurements.

Keywords: microwave reflectometer, uncertainty, Kalman filter, signal flow graph.

Modelowanie wpływu odbić sensorów na dokładność pomiaru reflektometrem mikrofalowym

Streszczenie

Artykuł przedstawia i porównuje wyniki modelowania błędów granicznych w pomiarach mocy sygnału mikrofalowego w falowodzie wielosensorowym reflektometrem. Wyniki te uzyskano metodą najmniejszych kwadratów lub też filtrem Kalmana. Stosowanie kilku dodatkowych sensorów w falowodzie umożliwia pomiary trzech podstawowych parametrów mocy sygnału ze zwiększoną czułością. Jednakże sensory oddziałują wzajemnie na siebie. Analizuje się jednorzędowy i dwurzędowy układ rozmieszczenia sensorów podany na rys. 1a,b. Odległość między sensorami odpowiada 1/8 długości fali w falowodzie. Wykorzystując grafy skierowane opracowano model przepływu sygnałów w układzie - rys. 2. Uwzględniono wpływy odbić od sąsiednich sensorów rozmieszczonych w falowodzie. Otrzymano uproszczony liniowy układ równań algebraicznych uwzględniający podstawowe oddziaływania odbić od sensorów - wzór (2). Przy założonych wariancjach dla normalnych rozkładów zakłóceń w torach czujników oszacowano standardowe niepewności pomiarów mocy sygnału w falowodzie. Użyto uśredniania metodą najmniejszych kwadratów MNK lub filtru Kalmana, dla którego podano schemat przetwarzania - rys. 3 i wzory (3)-(10). Niepewności uzyskane obiema metodami dla różnych przesunięć fazowych pomiędzy sensorami i różnej ich liczby przedstawiono na rysunkach 4 i 5. Porównano otrzymane wyniki. Stosując większą liczbę czujników niż 3 obiema metodami uzyskano kilkuprocentowe zmniejszenie standardowej niepewności pomiarów mocy mikrofalowego sygnału w falowodzie. Metodę filtru Kalmana można wykorzystać nie tylko przy automatyzacji pomiaru reflektometrem wielosensorowym, ale i do powiększenia dokładności innych wielosensorowych pomiarów procesów z zakłóceniami.

Słowa kluczowe: reflektometr mikrofalowy, niepewność pomiaru, filtr Kalmana, graf przepływu sygnałów.

1. Introduction

In the last years, the microwave measurements have been rapidly evolving and reaching higher and higher range of frequencies. That depends on development of the digital and microprocessor technique based instruments. However, the basic underlying concepts, such as applied in network analyzers and calibration, still even constrain the development of more modern equipment.

In recent years, microwave instrumentation have to meet new testing requirements for 3G and now LTE wireless networks, for millimeter wave and THz applications. Work in time and frequency domains has to be possible in one extensive approach. S-parameter measurements have been moving towards the development of a multi-sensor reflectometer with a multi-channel transmission structure and data digital presentation. New calibration procedures and the instrument architecture have been introduced to improve accuracy, versatility and speed of work [1].

Vector scattering parameter measurement is a standard procedure in RF and microwave electronics. Commercial vector network analyzers are usually used for this purpose. However, in some cases, where this way is not applicable or not economic, some other methods can be used. This paper deals with one of the alternative methods, which is based on the six-port reflectometer. This reflectometer system has many applications today. The simple RF hardware of the system is the main advantage. The vector value of the reflection coefficient is computed on the basis of several (four) scalar values. The reflection coefficient is then computed by the appropriate method. The number of sensors in the multi-probe reflectometer is higher than the number of measured parameters. Additional sensors allow getting higher sensitivity and accuracy [2].

On the one hand, the distance between the adjacent sensors is chosen as 1/8 part of microwave length λ_w to reduce the mismatch error (caused by reflection from the load of a transmitting line). On the other hand, due to mutual influence of reflections between sensors, the additional error of the output signal exists. However, reducing the mismatch error even at the presence of the error from sensor reflection is justified because the value of the latter is less than that of the mismatch error.

So, in the analysis of the measurement accuracy of the multiport microwave reflectometer one must pay attention to error components caused by the mutual influence of reflection between sensors. This problem can be regarded as similar to that which occurs in antenna arrays [3], and is accounted for the "induced EMF". The measurement uncertainty due to the mutual influence of electro-magnetic fields of sensors is especially important if they are at a distance that does not exceed the boundary of the far zone. Investigators have recently begun to study mutual resistance between the two probes vertically arranged on the broad wall of a rectangular waveguide. Study of the field distribution of the sensor and the formula of mutual impedance between two of them vertically located in the waveguide wall is given in detail in paper [4].

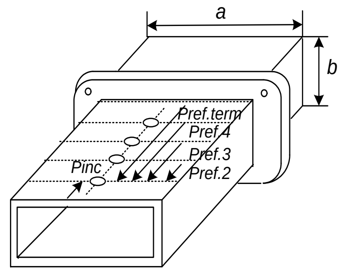
The aim of this paper is a comparative analysis of the accuracy of the multiport microwave reflectometer, taking into account the mutual reflections between probes. The processing of sensor signals is based on the method of least squares or Kalman filtering. Varied location of sensors and their number are considered in this study.

2. Essence of the problem

Two cases of the sensor positions in the waveguide are considered. In the first case the sensors are located in the middle of the wide wall along the direction of propagation of energy (Fig. 1a). The scheme of a two-line placement of the sensors in the waveguide broad wall is shown in Fig. 1b. In both cases the distances between the adjacent sensors are identical and equal to $\lambda_w/8$.

The sensor signals consist of the measured wave and the waves reflected from other sensors. For example in Fig. 1a. there is shown that the first sensor obtains reflections from the second, third and fourth sensor. The incident and reflected signals should be also considered at the other sensors planes. Altogether there are five terms in the expression of the output voltage of each sensor.

a)



b)

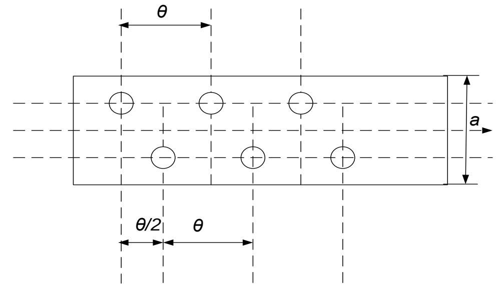


Fig. 1. Arrangements of the sensors in the waveguide: a) four sensors in one line, b) sensors in two lines

Rys. 1. Rozmieszczenie czujników w falowodzie: a) cztery czujniki w jednej linii, b) czujniki w dwu rzędach

3. Mathematical model

The theory of signal flow graphs allows calculating the gain using the nonintersecting loops rule of Mason [5]. Figure 2 presents the model signal flow of a four-sensor section under the assumption of the cascade connection of sensors and the waveguide sections without sensors. The model is obtained based on the scattering matrix of the sensors. It is assumed that the sensor is a reversible element, i.e. the gain of the graph from the input to the output and back is the same.

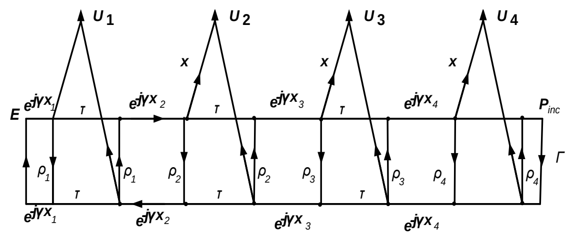


Fig. 2. Flow graph for four sensors including reflections

Rys. 2. Graf przepływu sygnałów z odbiciami dla czterech czujników

Factor $e^{-j\gamma x}$ is the ratio of the signal in two points located at distance *x*, $\gamma = 2\pi\,\lambda_w^{-1}$ is the propagation constant and λ_w - the wavelength in the waveguide. Then the phase distance between the sensors is

$$\theta = 2\gamma x = 4\pi x\,\lambda_w^{-1}$$

The model of signal flows from Fig. 2 is applied to calculations described below with some simplifications.

- First: loops of higher order are neglected since reflections ρ_i from all sensors are small ($\rho_i \equiv \rho = 0.05$).
- Second: all multipliers $e^{-j\gamma x_i}$ are identical. Not all of the first order loops are counted, but only those with the minimal number of $e^{-j\gamma x}$. Multiplication of two is much less than 1. So with increasing number of these factors all products asymptotically approach zero.

- Third: there is assumed that the sensors have the identical sensitivity.

The signal of the single sensor is

$$P_i = P_{\mathrm{inc}}[1+\Gamma^2 + 2\Gamma\cos(\varphi)] = P_{\mathrm{inc}}(1+\Gamma e^{-j\varphi})^2 = P_{\mathrm{inc}} + P_{\mathrm{ref}} \quad (1)$$

where: P_{inc} – incident power, P_{ref} – reflected power, Γ – module of the load reflection coefficient, φ – phase of the reflection coefficient of the sensor.

The system of equations, covering reflections from the load and from the sensors on the way of distribution of the reflected wave, is

$$\begin{cases} P_1 = P_{\mathrm{inc}1} + P_{11} + P_{41} + P_{31} + P_{21} \\ P_2 = P_{\mathrm{inc}2} + P_{22} + P_{42} + P_{32} \\ P_3 = P_{\mathrm{inc}3} + P_{33} + P_{43} \\ P_4 = P_{\mathrm{inc}4} + P_{44} \end{cases} \quad (2)$$

where: $P_{\mathrm{inc}1}$– signal incident on the first sensor from the generator; P_{11} – signal reflected from the load falling on the first sensor; P_{41}– signal reflected from the fourth sensor and got on the first; P_{31} – signal reflected from the third sensor and got to the first sensor. The same is true for other sensors.

4. Algorithms of the simulation process

The performance of the multi-port reflectometer is degraded by the presence of noise and other random distributions. The uncertainty of the output signal may be significantly reduced by employing signal processing with the method of least squares or a Kalman filter. The condition of applicability of both these methods is the redundant system of linear equations, i.e., when there are more equations than the number of independent variables to be measured.

Application of the least squares method has advantages over the method based on the solution of the set of linear algebraic equations. The ability to handle data from a large number of sensors with errors is possible. The least squares method can be used for the multi-sensor reflectometer [6], but an influence of mutual reflections of sensors has not been yet considered in detail. The method of least squares can be applied under the assumption that the variables are independent and have the multidimensional normal distribution. In the case when the last requirement is a serious disadvantage the problem can be solved by the Kalman filter [7, 8].

In the described below method, a priori information source is the solution of linear equations for three sensors. It is obtained by linear algebra methods. To improve the accuracy, the processing of the sensor signal is complicated on the physical level. A fourth sensor is applied. The algorithm for processing the signals of the system with redundant sensors by the Kalman filter method is proposed in [7, 8]. The scheme of processing signals of four sensors is presented in Fig. 3.

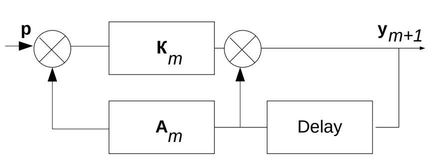


Fig. 3. Model of signal processing by the discrete Kalman filter
Rys. 3. Model przetwarzania sygnału przez cyfrowy filtr Kalmana

The algorithm describing the recursive processing of the signal, as in Fig. 3, is obtained from the matrix equation

$$\mathbf{y}_{m+1} = \mathbf{y_0} + \mathbf{K}(\mathbf{p} - \mathbf{A_1}\,\mathbf{y}_m) \quad (3)$$

The formulas describing the parameters in Eq. (3) are

$$\mathbf{y}_m = \begin{bmatrix} P_m \\ (\Delta P\cos\varphi)_m \\ (\Delta P\sin\varphi)_m \end{bmatrix} \quad (4) \qquad \mathbf{y_0} = \begin{bmatrix} \dfrac{-P_1 + 2P_2\cos\theta - P_3}{2(\cos\theta - 1)} \\ \dfrac{P_1 - 2P_2 + P_3}{2(\cos\theta - 1)} \\ \dfrac{P_1 - P_3}{2\sin\theta} \end{bmatrix} \quad (5)$$

$$\mathbf{p} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} \quad (6) \qquad \mathbf{K} = \left(\mathbf{M}^{-1} + \mathbf{A_1}^{\mathbf{T}}\mathbf{R}^{-1}\mathbf{A_1}\right)^{-1}\mathbf{A_1}^{\mathbf{T}}\mathbf{R}^{-1} \quad (7)$$

$$\mathbf{A_1} = \begin{bmatrix} 1 & \cos 3\theta & \sin 3\theta \\ 1 & \cos 2\theta & \sin 2\theta \\ 1 & \cos\theta & \sin\theta \\ 1 & 1 & 0 \end{bmatrix} \quad (8) \qquad \mathbf{R} = \begin{bmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{bmatrix} \quad (9)$$

$$\mathbf{M} = \begin{bmatrix} \dfrac{\sigma_1^2 + 4\sigma_2^2\cos^2\theta + \sigma_3^2}{4(\cos\theta - 1)^2} & 0 & 0 \\ 0 & \dfrac{\sigma_1^2 + 4\sigma_2^2 + \sigma_3^2}{4(\cos\theta - 1)^2} & 0 \\ 0 & 0 & \dfrac{\sigma_1^2 + \sigma_3^2}{4\sin^2\theta} \end{bmatrix} \quad (10)$$

where in Eqs. (3) -(10): $\mathbf{y}$ -output signal, $\mathbf{y_0}$ -initial approximation of $\mathbf{y}$, $\mathbf{p}$ -one column vector of sensor signals, $\mathbf{K}$ -transmittance of the Kalman filter, $\mathbf{A_1}$ -matrix of equations of the system with four equidistant sensors, $\mathbf{R}$ -variance and covariance matrix of the sensor random errors, $\mathbf{M}$ -matrix of a priori covariance of the errors obtained from indirect measurements.

Variance elements σ_i^2 are located at the principal diagonal of matrix $\mathbf{R}$. All covariances, as its off-diagonal elements, are equal to zero. Standard uncertainty σ_i is the standard deviation of the distribution of the random errors of the i -th sensor channel. Matrix $\mathbf{M}$ is obtained from the expression (10).

Unknown parameters, that is, the power and the reflection coefficient will be expressed in terms of the intermediate variables from equations (4) and (5). The expressions for the passing incident and reflected power, the module and phase of the reflection coefficient can be obtained by using their definitions [9].

The passing power is

$$P_{pas} = \sqrt{P^2 - (\Delta P\cos\varphi)^2 - (\Delta P\sin\varphi)^2} = \sqrt{\left(\frac{0.5(P_1 + P_3) - P_2\cos\theta}{1 - \cos\theta}\right)^2 - \left(\frac{P_1 + P_3 - 2P_2}{2(\cos\theta - 1)}\right)^2 - \left(\frac{P_1 - P_3}{2\sin\theta}\right)^2} \quad (11)$$

where $P = P_{inc}(1+\Gamma^2)$ and $\Delta P = 2\Gamma P_{inc}$ are intermediate variable or

$$P_{pas} = \sqrt{(P - \Delta P\cos\varphi)(P + \Delta P\cos\varphi) - (\Delta P\sin\varphi)^2} = \sqrt{P^2 - (\Delta P\cos\varphi)^2 - (\Delta P\sin\varphi)^2} \quad (12)$$

where $P + \Delta P\cos\varphi = P_2$,

$$P-\Delta P\cos\varphi=\frac{2P_2\cos\theta-P_1-P_3}{2(\cos\theta-1)}-\frac{P_1+P_3-2P_2}{2(\cos\theta-1)}=$$
$$=\frac{2P_2(1+\cos\theta)-2P_1-2P_3}{2(\cos\theta-1)}.$$

The incident power is

$$P_{inc}=0{,}5(P+P_{pas}) \quad (13)$$

The modulus of the reflection coefficient is

$$\Gamma=\frac{\sqrt{(\Delta P\cos\varphi)^2+(\Delta P\sin\varphi)^2}}{P_{inc}} \quad (14)$$

The phase of the reflection coefficient is

$$\varphi=arctg\frac{(P_3-P_1)\,(\cos\theta-1)}{(P_1+P_3-2P_2)\,\sin\theta} \quad (15)$$

or

$$\varphi=arccos\frac{P_2-P}{\sqrt{(\Delta P\cos\varphi)^2+(\Delta P\sin\varphi)^2}} \quad (16)$$

5. Results of simulation

As the metrological model of the relative extended uncertainty for the passing power measurement taken there is

$$U_r(P)=\frac{|P_{pas0}-P_{pas}|}{P_{pas0}}100\% \quad (17)$$

where P_{pas} is from (11), $P_{pas0}=P_{inc}(1-\Gamma^2)$ is from the definition.

Simulation calculations were performed for both even and odd number of sensors. The reference point was chosen at the last seventh sensor. Calculations were performed for the phase θ in the range from 0.5π to $2\pi/3$, which did not go beyond the bandwidth of the waveguide. Moreover, the extreme points of θ themselves are of interest, as they are referred to as the optimal placement of sensors at a fixed frequency. The modulus of the reflection coefficient of load $\Gamma=0.4$, the phase of the reflection coefficient $\varphi=0.25\pi$, the standard deviation in the sensor signal $\sigma<0.02$.

The dependence of the relative uncertainty U_r of power P on the phase distance θ for a different number of sensors and two types of placement is shown in Fig. 4a,b. The curves were obtained from the calculations using the method of least squares or the Kalman filter.

From the measurement results shown in Fig. 4b it follows that at $\theta=2\pi/3$ processing with the Kalman filter for N=5 sensors is preferable. Almost everywhere the uncertainty U_r is smaller for a greater number of sensors. The exception is at the phase distance of 2.1 radians for five sensors, where the smallest uncertainty value is obtained. It is explained by the diverging of the iterative process (the Kalman filter refers to the iterative processes). The uncertainty reaches the minimum and further increase in the number of sensors is impractical.

The analysis of research on the relative uncertainty U_r of the power measured by sensors of the two-line location (as in Fig. 1b), shows that the uncertainty depends on the first approximation of the Kalman filter method. In this case and for the same number of sensors as of one-dimensional location, the relative uncertainty U_r is greater. It is due to the reflection of signals especially for centrally located sensors. The dependence of the relative uncertainty $U_r(P)$ of the passing power on the number of sensors is shown in Figure 5a,b.

a)

b)

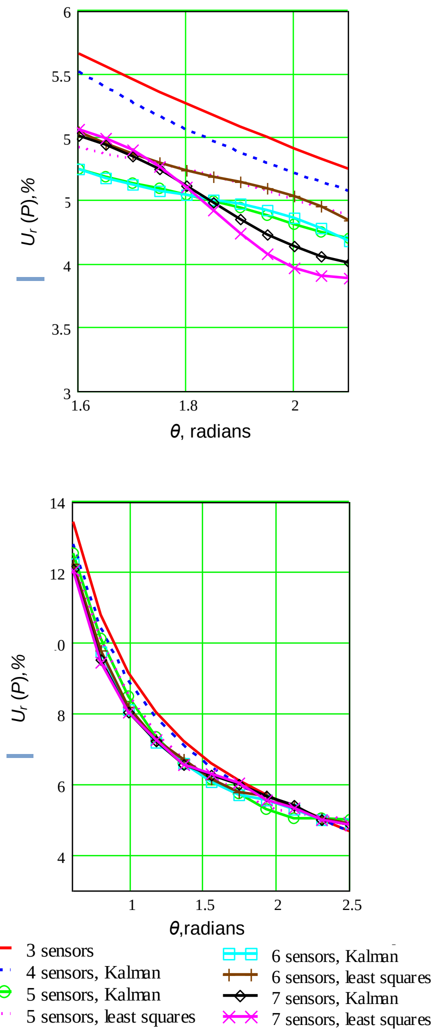


Fig. 4. Dependence of the extended uncertainty $U_r(P)$ of the measured power P on the phase distance θ between the sensors placed: a) in one line and b) in two lines

Rys. 4. Zależność niepewności rozszerzonej $U_r(P)$ dla pomiaru mocy P od różnicy faz θ sygnału sensorów umieszczonych: a) w jednej linii, b) w dwu rzędach

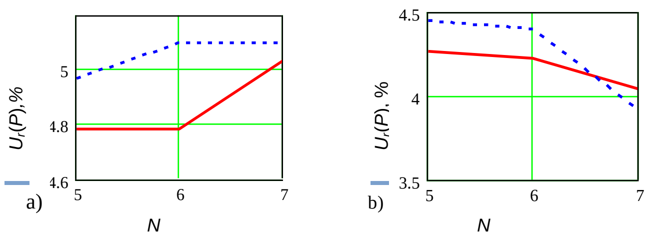


Fig. 5. Dependence of uncertainty U_r on the arrangement and number of sensors. The phase distance between the adjacent sensors: a) $\theta=0.5\pi$, b) $\theta=2\pi/3$; $U_r(P)$ – relative standard uncertainty of passing power, N – number of sensors, Kalman filter, least square

Rys. 5. Zależność niepewności pomiarów U_r od liczby czujników dla przesunięcia fazowego między sąsiednimi czujnikami a) $\theta=0.5\pi$; b) $\theta=2\pi/3$. $U_r(P)$ – względna niepewność mocy sygnału, N – liczba sensorów, z filtrem Kalmana, metoda najmniejszych kwadratów

The fixed phase distance $\theta=2\pi/3$ is preferable for the measurement process when the Kalman filter is used. Then the relative uncertainty U_r for N=5 is near 4.5%, and for N=7 is 2% lower than U_r obtained by the method of least squares (Fig. 5b).

6. Conclusions

The simulation of the dependence of the relative uncertainty of the microwave reflectometer with seven sensors from the phase distance θ, obtained by the models: "with Kalman filter" and "method of least squares" shows that the processing of the measurement results by the Kalman filter gives the lower relative uncertainty. When $\theta = 2\pi/3$ (i.e. $\theta \approx 2.1$) the method of "Kalman filter" slightly (of about 5%) reduces the relative uncertainty U_r.

The range of angle $0.5\pi \le \theta \le 2\pi/3$ is preferred.

The both described methods (least squares and Kalman filter) of the uncertainty evaluation can be applied to automation of the measurement process of the multi-sensor reflectometer and may be implemented also in other multivariable measurements.

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