Techniques of Measuring Reflectance in Free Space in the Microwave Range

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***Abstract*—Results of metal plate reflection coefficient estimation using experimental data obtained under variation of the distance between object and the aperture plane of measuring antenna in the form of a pyramidal horn with application of 3-probe meter and neural network for calibration are presented. Parametric spectral analysis in sliding windows was applied.**

Keywords—reflection coefficient; neural network; parametric spectral analysis; microwave measurements

I. Introduction

Measurement of reflectivity of objects in free space is basis for solution of problems of non-destructive testing of products of dielectric materials [1, 2]. The knowledge of local complex reflection coefficient in specific points of an object is useful for estimation of the object total reflectivity, for instance radar cross-section. The application of these approaches requires the measurement of the complex reflection coefficient at grid of frequency in wide band. Holographic approach in frequency-time domain [3, 4] with corresponding windowing in time domain provides the requiring information using the simplest measuring equipment such as the scalar reflectometer. The use of direct and inverse Fourier transforms gives rather large corruptions of the recovered complex reflectance at the edges of frequency band. This approach can be improved by extrapolation of the experimental data in frequency domain using the principle of minimum duration [5, 6] or application of digital parametric spectral analysis [7]. The holographic approach in frequency-time space was successfully implemented in the series of measuring complexes [8 – 10] operating in frequency bands of 8-12, 17.4-25.9, 26.0-37.5, 38-52, and 126.6-145.4 GHz. The duration of synthesized pulses of 70 ps and level of reflection in free space of -25 dB were achieved that provided possibility to measure the reflection of such little reflecting and dynamic structures as foams [11, 12].

Now six-port meter [13] is prevalent for carrying out measurements of complex reflectivity [13]. It can be considered as an advanced version of the discrete holography with colliding beams. This conception is the most evident for 4-probe measuring section. The scheme based on E-plane waveguide cross [8] was proposed by V.A. Karlov. The cross structure similar to Michelson interferometer was successively applied in millimeter wave range for measurements of reflection coefficient in free space due to low level of own reflection in aperture of the open-ended waveguide [14]. Unfortunately, the traditional scheme with a horn does not allow obtaining correct results. In fact, the six-port meter implements a holographic processing with three reference signals [15], there may be formed a special system of linear algebraic equations. This approach makes it possible to analyze the accuracy characteristics for different schemes based on the analysis of the condition number of the corresponding matrix with dimension of 2×2 and apply well-known means of regularization in a system of linear equations. Quadratic characteristics of detectors can be effectively obtained due to neural network application [16].

The determinative feature of multifrequency method providing the possibility to measure complex reflection coefficient is the variation of electrical distance between the aperture and the object planes. This variation can be fulfilled directly by variation of distance. This idea was realized in [14] for the measurements with scalar reflectometer. For measurements in free space required reference discontinuity is provided due to reflection from open end of the waveguide [17]. The dependence of field amplitude versus distance can be successively described with the spherical wave model.

The purpose of this paper is to implement the approach [7] for experimental data obtained under variation of the distance between object and the aperture plane of measuring antenna in the form of a pyramidal horn with application of 3-probe meter and neural network for calibration.

II. Application of a Neural Networks for Probe Detector Calibration

The success of data processing in accordance with the holography principle is driven by the accuracy of coincidence of real detector characteristics with quadratic function. So, if the output detector characteristic is not quadratic, the calibration dependence for recalculation of an output detector signal is need. Traditionally, the standard dependence of reflectivity in the form of $\sin^2 x$ is used. This dependence is true for the output signal of an ideal detector connected with a probe positioned in a waveguide terminated with a slide short-

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circuited piston with $x = 2\pi z/\Lambda$, Λ is the wavelength in the waveguide and z is the distance from the probe to the piston. It is clear that normalized points lie in interval from 0 to 1.0. The number of experimental points was 11. They were obtained with step 1 mm in the range 10 mm. The model of corresponding dependence was constructed with application of neural networks.

The first stage of investigation was the application of feed-forward backpropagation neural network as in [16]. The structure of the basic network contained 4 neurons in the hidden layer, and 1 neuron in the output layer. The later neuron had the activation function in the form of sigmoidal function of type 'logsig'. Although the mean value of standard deviation per measured point was 0.004, the mean value of standard deviation per point in intermediate intervals between measured points was 0.008 that is twice greater than previous one.

Application of approximating neural feed-forward network with configuration coinciding with the previous one allowed to obtain the mean value of standard deviation per point equal to 0.0051, and the mean value of standard deviation per point including intermediate intervals was 0.0054.

The neural network the most adequate for approximation problem solution is the radial basis network. For the first step the network with the same structure was under consideration. The spread parameter was chosen equal to 2. The calibration dependence in this case had the mean value of standard deviation per experimental point equal to $7.8 \cdot 10^{-8}$, and the mean value of standard deviation per point in intermediate intervals was 0.0036 that was much less than for all previous neural networks.

The shape-preserving piecewise cubic interpolation for obtaining data in intermediate intervals between measured points was used for diminishing the residue of calibration dependence produced by the neural network and experimental dependence. In the range of piston sliding the number of points for training the neural network was increased from 11 to 101 with step 0.1 mm. This procedure was accompanied with growing the number of neutrons in the hidden layer to 20 neurons.

The use of this approach for approximating neural feed-forward network reduced the standard deviation of the neural network output from model data in support (measured) points to 0.00054. If it took into account the intermediate points, the standard deviation of the network output from model data was 0.0027 per one point.

This approach proved its higher level of effectiveness for application to approximating neural radial basis network. The interpolated intermediate values were used only on stage of creating of the neural network. The neural radial basis network training was based only on measured (support) values. The parameter ‘spread’ was chosen 1.5. In this case, after training standard deviation of residue of the neural network output from the model data in support (measured) points was $4 \cdot 10^{-7}$, with accounting the intermediate points the standard deviation of network output from the simulated data was 0.0005 (more 5 times less than result for feed-forward network and more 7 times less than result for this network in the previous case). At the same time, creating and training the network was 10 times less than for the previous case. The result of this neural network working is presented in Fig. 1, 2.

Therefore, the neural network with radial basic-activation functions created with use of the interpolated values of the mentioned calibration dependence was chosen for experimental data processing. Additionally, to enhance the effectiveness of this approach, the initial value of the width of the radial function (parameter ‘spread’) was determined using an optimization procedure to select the value providing minimum mean square deviation of the residue of the creating neural network output from data used for calibration.

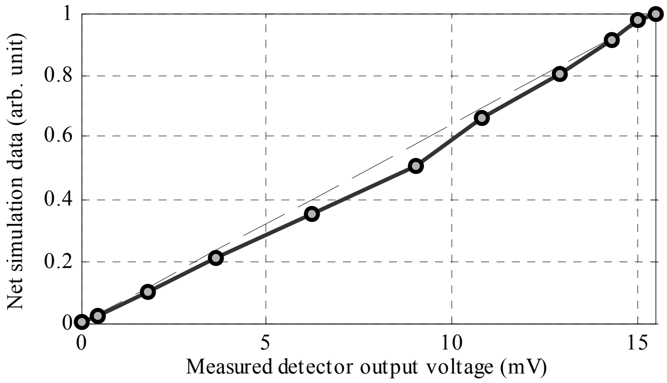

Fig. 1. The calibration curve for radial basis neural network.

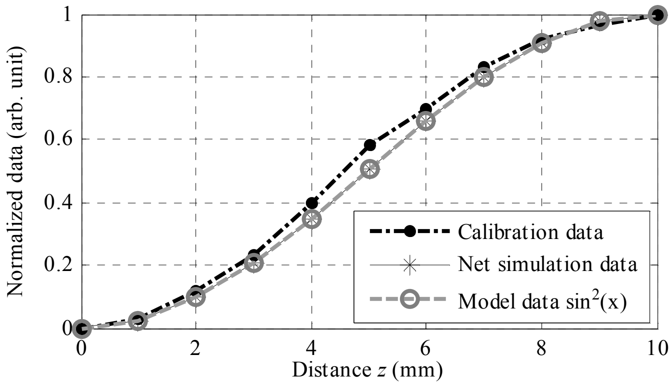

Fig. 2. The results of calibration curve implementation for radial basic neural network and application the interpolation procedure.

III. Experimental Rezults and Discussion

The measurements of reflectivity of a test sample in free space with variation of the distance between the test sample and the measurement antenna aperture plane with three/four-probe reflectometer on base a waveguide with the cross section of 23 × 10 mm were carried at the frequency of 10 GHz. A pyramidal horn with an aperture size of 95 × 95 mm and the length of 200 mm was used as the measurement antenna. The variation of the distance between the test sample and the aperture plane was enclosed in the range from 300 to 450 mm. The complex insert reflection coefficient of a plane metal plate obtained according the approach of holographic processing [16] in combination with neural network calibration is presented in Fig. 3, 4. From experimental data it is clear that direct application of this data accompanied with error of ±15 %. Fig. 5 shows the Fourier spectrum of obtained experimental data. For convenience, the x-axis is presented in units of frequency instead of wave number or wavelength. The peak 1 in the origin is determined by the reflection really from the horn. This reflection was equal to approximately 0.03. It is evident that the peak 2 is corresponding to frequency of electromagnetic radiation of 10 GHz. The amplitude of this peak is equal to 0.24 that is the average value of the dependence measured. The peak 3 describes the first reverberation and its position is rather close to 20 GHz. The second reverberation (the peak 4) has relatively small amplitude and can be observed at position of 30 GHz. It is clear that neglecting the reverberation effect involves the error of approximately 20 %.

The main peak at 10 GHz determines the reflection actually from the object. This peak can be retrieved by filtration with Butterworth filter function. This function is preferable since it has not oscillations in the pass-band. Band-pass Butterworth filter of order 8 with the pass-band of 5-13 GHz was chosen for solution of this problem. The results of transformation the retrieved peak into space domain are presented in Fig. 3.

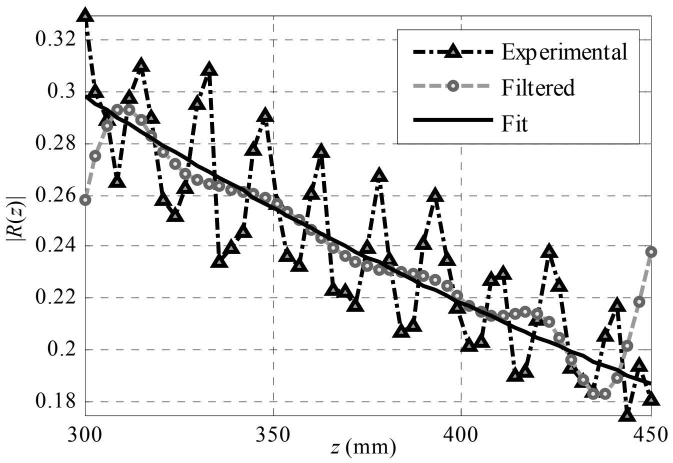

Fig. 3. The experimental dependence of the insert reflectance modulus for plane metal plate against the distance between the plate and the aperture plane, the result of its filtering with band-pass Butterworth filter of order 8, and fitting by the single exponential function.

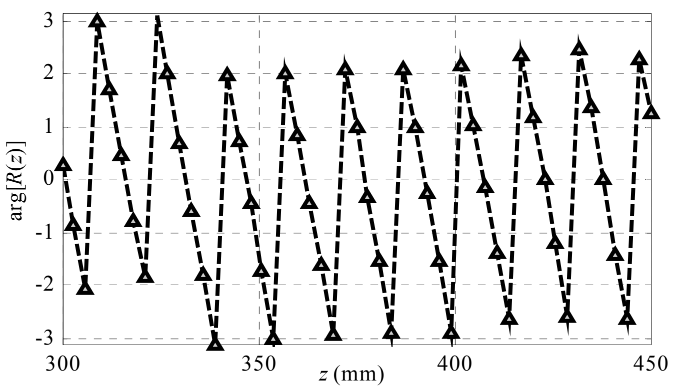

Fig. 4. The phase of experimental insert reflection coefficient of plane metal plate versus the distance between the test sample and the aperture plane.

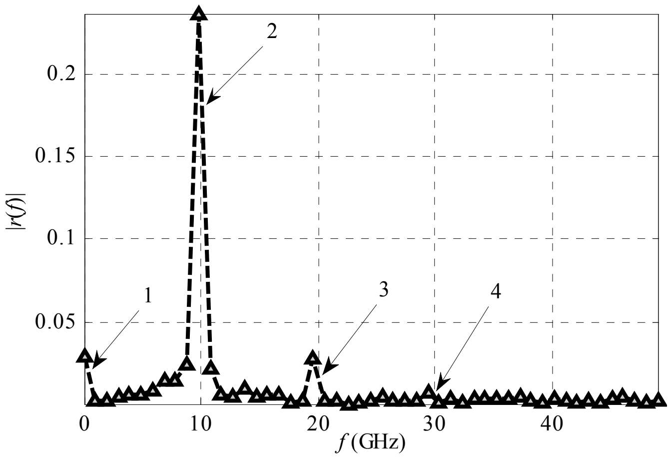

Fig. 5. The spectrum of insert complex reflection coefficient of plane metal plate versus the distance between the test sample and the aperture (x-axis is recalculated in units of frequency).

Similarly to the traditional filtration large distortions at the edges of range are observed. It is interesting to note that phase of raw experimental and filtered data are practically coincided. The presence of changes in the insert reflectance with variation of distance determines the necessity of application sliding spectral analysis with help of window Fourier transformation. The most evident is application of sliding rectangular window. The dependence of the value of spectral maximum $a(z)$ for every window as function of the distance between the aperture plane and the plate for the window length of $L = 15$ is shown in Fig. 6. This dependence has not so large distortions at the edges but in the central part it is not smooth enough and the level of oscillations is higher than it for previous case.

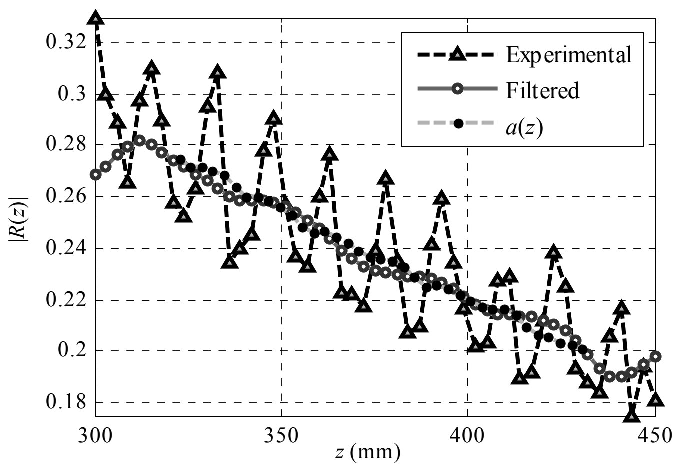

Fig. 6. The dependence of the raw experimental reflectance data against the distance to the plate and the result of filtering after application of the window Fourier transform for $L = 15$. The dependence of the maximum sample for every window of the window spectrum against the distance to the plate for window length of $L = 15$.

Filtering by bandpass Butterworth filter of order 8 with the bandwidth of 5-13 GHz was successful for window Fourier transform with window length $L = 5k$, $k = 2,3,4$, because the quasiperiod of the dependence was 5 samples. Under these conditions the maximum gets in bin of discrete Fourier transform. The filtered data is shown in Fig. 6.

The parametric spectral analysis [18] allows to estimate complex frequency, thus exponential model with order 1 describes the space dependence of reflectivity with variation of distance to object. Removal of the component with frequency near to 0 by subtraction the measurement results for radiation into free space simplifies the analysis of the considered dependence and improves the accuracy of estimates. The corresponding complex exponent was equal to (9.86, -0.074) GHz. It is interesting that real part did not strictly coincide with 10 GHz. This fact can be explained due to presence of plane wave space spectrum of a horn radiation. It is expected that difference between reverberations has to be less. Indeed, growing the model order to 10 gave corresponding frequencies of 19,55 and 29,14 GHz and the differences were 9,69 and 9,59 GHz. The consideration of single exponential function with complex exponent is similar to the filtration of the main peak. Corresponding results are shown in Fig. 3.

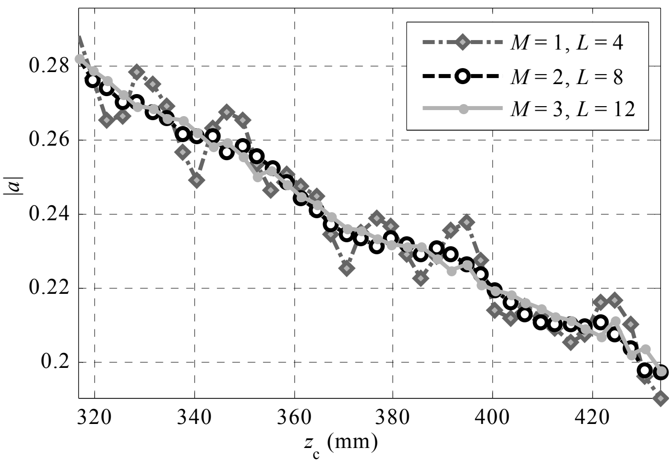

Fig. 7. Dependence of the main spectral peak amplitude against the sliding window center location for $L = 4M$.

The spectral analysis with quasisolution method was carried out in a sliding window with length of $L = 4M$. The error of approximation for entire dependence for M = 1, 2, 3 was 0.29%, 0.21%, and 0.11%. In the comparison, for entire dependence approximation and M=10 the error was 0.2%. The dependence of the magnitude of the main spectral peak, which determines the reflection from the sample under consideration, versus the center of the sliding window for different orders of the model is shown in Fig. 7. The reflections for convex and concave metal surfaces were under experimental investigation. The curvature radius was varied from 10 to 40 cm with step 5 cm. The reflection from the convex surfaces was twice less for radius of 10 cm than for plane surface but for concave metal surfaces coefficient was twice greater for radius of 30 cm than figure for plane one.

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