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MULTIFREQUENCY MICROWAVE IMAGES WITH INVERSE SYNTHETIC APERTURE IN THE INTERMEDIATE ZONE OF RADIATION

Experimental results of reflectivity measurements for a metal sphere with diameter of 35.5 mm in the range of 38-52 GHz at the grid of 256 frequencies are presented. Application of reference discontinuity in the form of an iris positioned in the throat of the horn allowed implementing the Fourier-holography principle and obtaining direct reflection from the sphere by Fourier transform of data in frequency domain. The magnitude of reflection directly from the sphere is proportional to its diameter. The method of inverse aperture synthesis on the basis of the generalized method of spatial inverse filtration is proposed. The peculiarity of inverse aperture synthesis implementation is this approach application to the result of the Fourier transformation of frequency data. For the real experimental data the spatial resolution was improved in 2 times by inverse aperture synthesis. The suggested method of data processing provided the possibility of forming the sphere radioimage.

Keywords: spatial resolution, inverse aperture synthesis, inverse filtration, microwave image

Подані експериментальні результати вимірювань характеристик відбиття для металевої сфери діаметром 35.5 мм у діапазоні 38-52 ГГц на сітці з 256 частот. Застосування опорної неоднорідності у вигляді діафрагми, яка розташована в горловині рупора, дозволило реалізувати принцип фур'є-голографії й отримати безпосередньо сигнал відбиття від сфери шляхом перетворення Фур'є даних вимірювань у частотній області. Амплітуда відбиття безпосередньо від сфери пропорційна її діаметру. Запропоновано метод оберненого синтезування апертури на основі методу узагальненої просторової інверсної фільтрації. Особливістю реалізації оберненого синтезу апертури є застосування його до результату перетворення Фур'є частотних даних. Для даних реального експерименту було досягнуто підвищення роздільної здатності в 2 рази шляхом застосування інверсного синтезування апертури. Запропонований метод обробки даних забезпечив можливість сформувати радіозображення сфери.

Ключові слова: просторова роздільна здатність, обернене синтезування апертури, інверсна фільтрація , мікрохвильове зображення

Представлены экспериментальные результаты измерения характеристик отражения для металлической сферы диаметром 35.5 мм в диапазоне 38-52 ГГц на сетке в 256 частот. Применение опорной неоднородности в виде диафрагмы, размещенной в горловине рупора, позволило реализовать принцип фурье-голографии и получить непосредственно сигнал отражения от сферы путем преобразования Фурье данных измерений в частотной области. Амплитуда отражения непосредственно от сферы пропорциональна ее диаметру. Предложен метод обратного синтезирования апертуры на основе метода обобщенной пространственной инверсной фильтрации. Особенностью применения обратного синтезирования апертуры является применение его к результату преобразования Фурье частотных данных. Для данных реального эксперимента было достигнуто повышение разрешающей способности в 2 раза путем применения обратного синтезирования апертуры. Предложенный метод обработки данных обеспечил возможность сформировать радиоизображение сферы.

Ключевые слова: пространственное разрешение, обратное синтезирование апертуры, инверсная фильтрация, микроволновое изображение.

1. Introduction

Radar methods are widely used in mechanical engineering and metallurgical industries to solve some technical issues in the relevant intellectual information and control systems [1]. Such applications induce some fundamental problems. The use of multi-frequency broadband signals ensures high resolution along the longitudinal coordinate. This resolution is determined by the bandwidth. Increasing the resolution can be achieved by applying the techniques of digital parametric analysis to data obtained through measurements in the frequency domain [2]. However, in many applications of microwave image processing it is necessary to achieve high resolution in the transverse plane. The traditional method of solving this problem is using synthetic aperture [3-5]. However, the classic synthetic aperture is applied to monochromatic signals. In some cases it is more convenient experimentally to apply an inverse synthetic aperture when the antenna does not move, but the object is moved. In such cases, the object is moved in the intermediate zone of radiation, this fact together with the broadband signal application requires additional studies.

The purpose of this paper is to obtain estimates of improving the spatial resolution in the transverse plane during the measurements in the frequency domain in a broad band in the intermediate zone of radiation using the concept of inverse synthetic aperture. The sphere with different values of radius has been chosen as standard object for investigation.

2. Samples and experimental setup

The purpose has been achieved experimentally with use of measuring equipment [6] in the range of 38-52 GHz. A pyramidal horn with the length of 120 mm and aperture sizes of 46×46 mm is used as radiating and receiving antenna and the source of reference signal for Fourier-holography principle implementation. The reflection in the horn throat was used as reference signal and served to save phase information. An iris was situated in the cross-section of the throat to increase the reference reflection. Synthesized pulses were obtained after transforming the measured frequency dependence to the time domain using the discrete Fourier transform. The synthesized pulse duration was equal to ~70 ps at the level of 3 dB thus space resolution was equal to ~2 cm. The further improvement of longitudinal resolution demands widening the operating frequency band. Fluctuations of the peak amplitude were less than 2%. It is well-known that for antenna with aperture size D for wavelength λ the far-field boundary R_2 is determined by $R_2 = 2D^2/\lambda$, but the intermediate-zone boundary R_1 is determined by $R_1 = 0.62\sqrt{D^3/\lambda}$. Thus, R_1 and R_2 are equal to ~70 and ~535 mm for the frequency of 38 GHz and ~130 and ~730 mm for the frequency of 52 GHz, respectively. Two spheres with diameters of 35.5 and 52.8 mm were chosen as objects under investigation. The distance between the aperture of the horn and the object under investigation was 200 mm that was intermediate zone of radiation.

3. Data processing

Traditionally, for aperture synthesis one uses Fourier or Fresnel transform in dependence if the object is in far-field or intermediate zone. But the problem becomes more complex if the object is situated in near-field zone. The inverse synthetic aperture approach is rather convenient for experimental implementation when measuring unit is stationary but an object is shifted along an axis which is perpendicular to the axis of radiation. The first step is the actual measurement of insert reflection coefficient of the object on the grid of frequencies. Such measurements are made for each position of the object, which is shifted laterally with 1 mm increments. Then Fourier transform of frequency dependences for each position of the object are carried out. The following step is selecting the informative fragment corresponding to the reflection from the object itself by windowing. The latter procedure eliminates reflections from surrounding objects and reflections in the antenna itself. For all transformations the time axis corresponds to the axis of the horn antenna radiation. Measurement unit along the mentioned axis can be chosen according to the linear relation $y = ct / 2$, where c is velocity of light in vacuum, and t is time variable resulting from the Fourier transform. Thereafter, for each value of the y-axis sample an array of data depending on the value of the transverse scan coordinate x is formed. Measurements for the reference object (copper vertical strip with width of 10 mm or 5 mm) are carried out in the similar scheme.

Inverse aperture synthesis with use of inverse filter transfer function with regularization was implemented according to the following expression

$$H(y, f_x) = \frac{S_E(y, f_x)}{E(y, f_x) + \alpha} \tag{1}$$

where $E(y, f_x)$ is the Fourier-image of the standard image of the copper strip of 5 or 10 mm width, $S_E(y, f_x)$ is Fourier-image of experimentally obtained radio image copper strip of 10 mm after pre-processing procedure, α is a regularization parameter.

It is assumed that the spatial image of the reference object in the form of a copper strip has the form of a rectangular function of the spatial coordinates x with the width which strictly coincides with the width of the copper strip.

Spatial signal spectrum in the case of synthetic aperture value for coordinate y is determined according to the method of mean geometric filtering [7], which is a generalization of the inverse filtering

$$S_A(y, f_x) = \left[\frac{1}{H(y, f_x) + \alpha}\right]^Z \left[\frac{|H(y, f_x)|^2}{|H(y, f_x)|^2 + \alpha}\right]^V S(y, f_x), \tag{2}$$

here $S_A(y, f_x)$ is a result of inverse filtering (after inverse Fourier transform we obtain the result of aperture synthesis), $S(y, f_x)$ is Fourier-image of experimentally obtained radio image for the object under consideration after pre-processing procedure, Z and V are regularization parameters varied in range [0, 1]. Really values of Z and V were equal to unit, y is the longitudinal coordinate, f_x is the spatial frequency for spatial x-coordinate. Such approach allows compensating not only phase distortion but magnitude one. The specific feature of the approach is the fact that the function against lateral coordinate is calculated not for single frequency but it is samples of inverse Fourier transform of frequency dependence in every point of lateral coordinate.

4. Results and discussion

The insert reflection for metal sphere of 35.5 positioned at the distance of 200 mm from the aperture of the horn was measured at the grid of 256 frequencies in the range from 38 to 52 GHz. In Fig.1 the directly measured data for 3 frequencies such as 38, 45 and 52 GHz are presented. The informative signal is corrupted by additional interference. The synthesized signal was calculated from the frequency data by inverse Fourier transform to time domain or after recalculation to space domain. Thus reflection against longitudinal axis was obtained. The modulus of this dependence for illumination of the central point of the sphere is presented in Fig. 2. This result can be considered as envelope of the synthesized radiopulse. The reflection from the sphere itself described by the peak 1 can be easily separated. The magnitude of this peak is equal to 0.00067 but the analogous magnitude for the sphere of the diameter of 52.8 mm was equal to 0.00098. The ratio of diameters was 1.487 and the ratio of the magnitudes was 1.463 that is rather

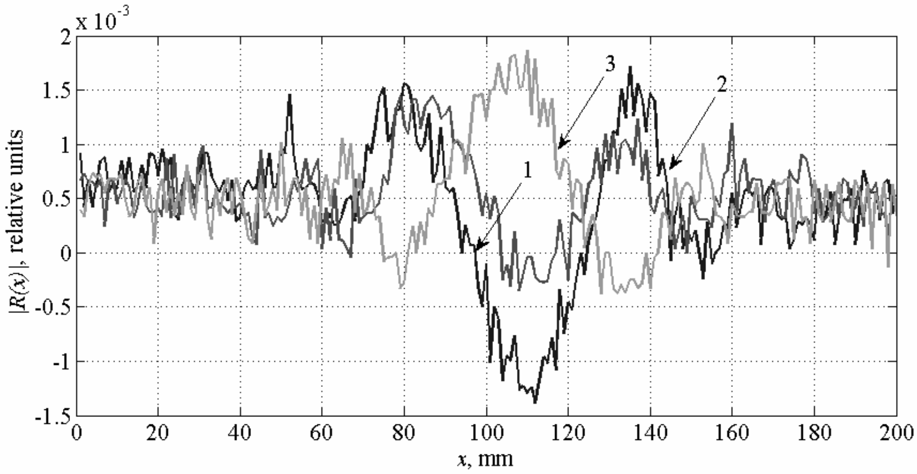

Fig. 1. The directly measured reflection from the sphere of diameter of 35.5 mm against lateral coordinate for frequencies 38 (1), 45 (2) and 52 (3) GHz.

close to the ratio of the diameters. Thus radar cross-section can be easily estimated if the value of standard sphere radar cross-section is known. After extraction of complex data in the vicinity of this peak and transformation to frequency domain signals refined from interference were obtained (Fig. 3). The signals of type presented in Fig. 2 were calculated for all positions along the lateral coordinate with step of 1 mm. For every value of *y* synthesized dependence as function of lateral coordinate *x* was formed. For *y* corresponding to maximum of *R(y)* the reflectivity against *x* is presented in Fig. 4. For

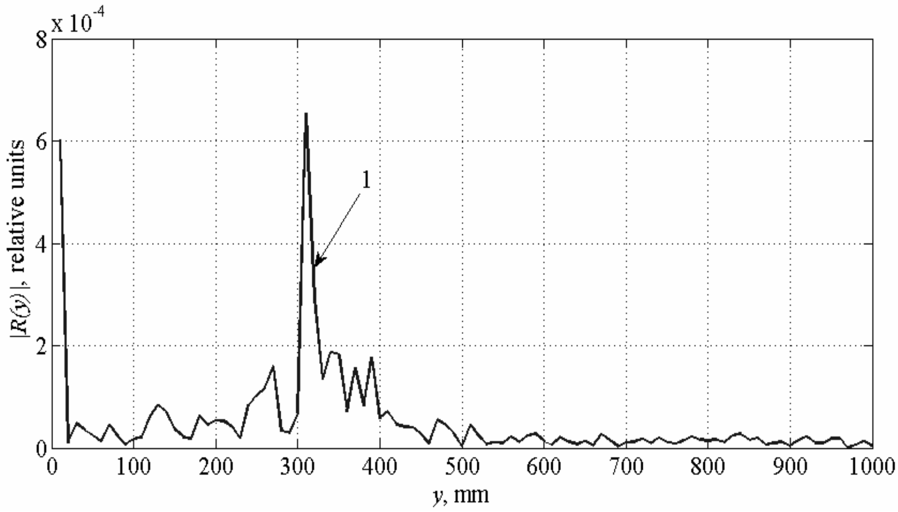

Fig. 2. The synthesized reflection against longitudinal coordinate with peak (1) of reflection from the sphere of diameter of 35.5 mm.

inverse aperture synthesis implementation the multifrequency measurements in combination with scanning along the lateral direction for copper strip with 10 mm width were carried out. The inverse aperture synthesis was calculated according to (2). The result of this procedure is presented in Fig. 4. It is clear that the peak compression is more than 2 times, thus the resolution is improved more than twice. The final radioimage is displayed in Fig. 5.

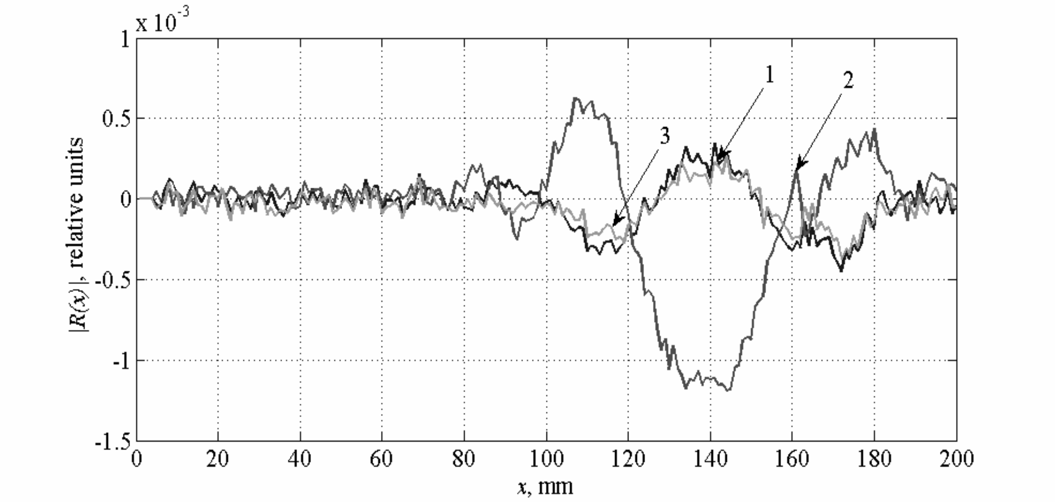

Fig. 3. The reflection from the sphere of diameter of 35.5 mm after extraction of reflection itself from the synthesized signal and inverse transformation to frequency domain against lateral coordinate for frequencies 38 (1), 45 (2) and 52 (3) GHz

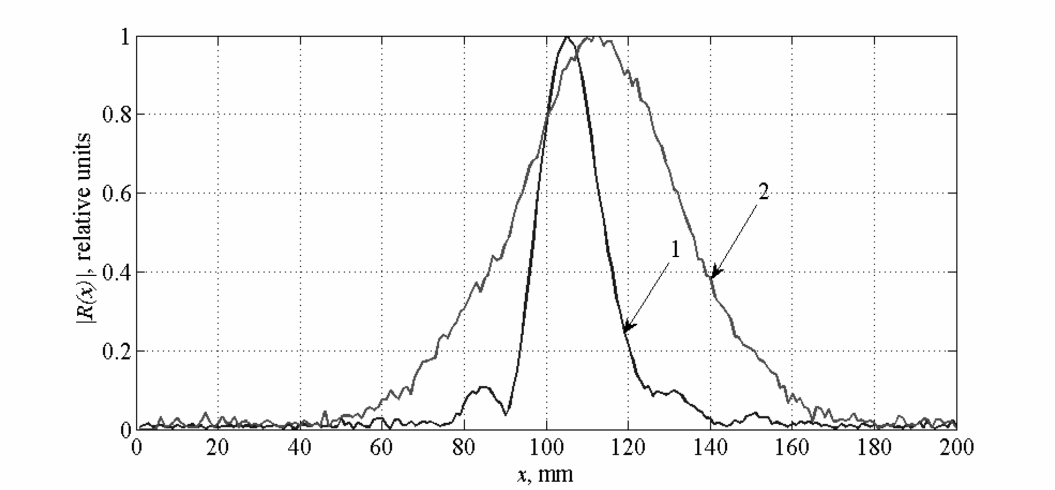

Fig. 4. The reflections in the position of peak corresponding to the reflection from the sphere itself against lateral coordinate for unprocessed data (1) and data (2) after inverse synthesis of aperture.

5. Conclusions

For real experimental data application of mean geometric filter as a generalized version of the regularized inverse filtering allows practically implementing the inverse aperture synthesis method. The reference signal measurement for a single strip provides results in the absence of mathematical models for the dependence of the amplitude and phase characteristics on the spatial coordinates. The proposed approach to experimental data allows improving the image resolution in the transverse direction compared with unprocessed experimental data more than twice.

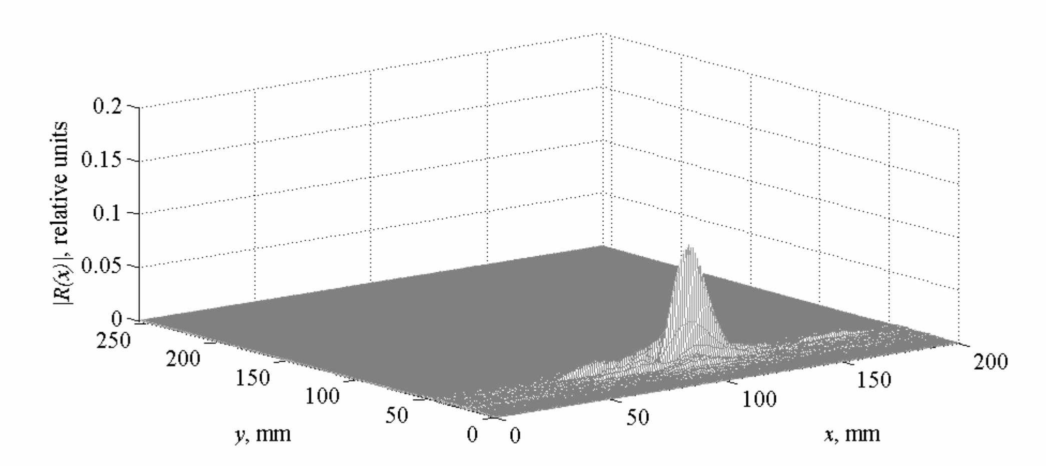

Fig. 5. The final radio image of the sphere after inverse synthesis of aperture

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