# 3-PROBE MICROWAVE MEASURING INSTRUMENT OF VIBRATION OF MECHANICAL OBJECTS WITH NON-PLANE SURFACE

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#### Abstract

Application of processing, which is specific to holographic concept with three reference signals, for complex reflection coefficient measurements by means of three-probe waveguide section is suggested. A mathematical model of diode detector on base of neural net is considered. The model provides a high level of square-law of output signal of detector and complex reflection coefficient measurements. The optimal model of neural net has structure of 1-4-1 neurons. For measurement of movement parameters estimation was done. As object of researches there was a metal concave and convex surface with various curvatures. For a decrease of a noise influence in the data, the Tikhonov's regularization method was used. Efficiency of the method has been proved experimentally.

*Keywords:* microwave reflectometry, microwave holography, neural network, 3-probe sensor.

# **1. INTRODUCTION**

Development of measuring means to estimate mechanical displacement and vibration parameters is a task of keen interest. Microwave methods have some advantages: they provide non-lag and non-contact measurements. Under conditions of heat treatment of product or presence of corrosive medium, the last fact is determinant for choice of microwave methods. Practical application of existing methods requires validity improvement that can be provided by application as traditional means as modern means of data processing, for instance neural network technologies [1].

Among microwave methods, interference method is the most popular one [2]. Examination of superposition of incident and reflected by object waves, which form standing wave in measuring waveguide, is foundation of the method. The set of detectors registers distribution of electrical field of the standing wave modulated by mechanical displacement of the object. From microwave measurements point of view the information of distance to object is contained in phase information of reflection coefficient.

Complex reflection coefficient  $\dot{\Gamma} = \Gamma' + j\Gamma''$  measurements is fundamental one for microwave engineering. Application of microwaves for non-contact measurements in free space demands use of waveguide elements. Modern vector analyzers are based on 6-port concept with hybrids [3], which are rather bulky construction for a waveguide version. In this respect probe waveguide sections have essential advantages. Really, traditional 4-probe waveguide section is 6-port transducer. For purposes of complex reflection coefficient measurements it is sufficient to use 3-probe measuring unit [3]. Classically the value of complex reflection

coefficient is the solution of the system of two quadratic equations; the last ones can be presented graphically as two circles. In classic works [4] the solution was founded using Smith chart, nowadays it is natural to use computer technology. It was noted that solution for reflection coefficient near to unity the solution had bad accuracy. All considered measuring devices can be considered as holographic devices with three reference signals [5]. This approach was successfully used for data processing in 6-port reflectometer on base of Eplane waveguide cross [6].

The goal of this paper is experimental investigation of displacement estimation accuracy by means of 3probe measuring waveguide unit.

## 2. HOLOGRAPHY CONCEPT APPLICATION

Let us consider three probes with detectors which are situated in a waveguide at distance of  $\lambda_g/8$  one from other,  $\lambda_g$  is wavelength in the waveguide. We suppose that detectors have square-law characteristic. The output signals of the detectors in the presence of load with complex reflection coefficient  $\dot{\Gamma} = \Gamma' + j\Gamma''$  can be expressed in the form

$$P_m = k_m \left| \exp(-j\psi_m) + \dot{\Gamma} \exp(j\psi_m) \right|^2, \qquad (1)$$

where  $\psi_m = \frac{2\pi}{\lambda_g} \frac{\lambda_g}{8} (m-1)$  and m = 1,2,3. The first

term in the right part of (1) can be considered as reference signals but the second term contains information about complex reflection coefficient  $\dot{\Gamma}$ . The coefficients of  $k_m$  for each detector can be removed from

concluding expression by dividing of measurement results (1) on measurement results in running-wave regime under conditions of matched load. Thus we have the system of three normalized quantities:

$$p_{1} = \left| \mathbf{l} + \dot{\Gamma} \right|^{2};$$

$$p_{2} = \left| e^{-j\frac{\pi}{2}} + \dot{\Gamma} \right|^{2};$$

$$p_{2} = \left| e^{-j\pi} + \dot{\Gamma} \right|^{2}.$$
(2)

According to the holographic approach with three reference signals [5] it is necessary to construct quantities  $p_1 - p_2$  and  $p_1 - p_3$ . The procedure of subtraction of the signal under conditions of matched load from each  $p_m$  can be omitted. As result the system of linear algebraic equations:

$$\begin{bmatrix} 4 & 0 \\ 2 & 2 \end{bmatrix} \begin{bmatrix} \Gamma' \\ \Gamma'' \end{bmatrix} = \begin{bmatrix} p_1 - p_2 \\ p_1 - p_3 \end{bmatrix}.$$
 (3)

can be obtained. The condition number for the system is equal to 2.618, in comparison the condition number of the system of linear algebraic equations for 4-probe measuring unit is equal to 1. It must be noted that the condition number does not depend on the value of reflection coefficient while the solution of the quadratic equation system by the classical method for reflection coefficients near to 1 produces large error. The solution of the system (3) can be written in the explicit form:

$$\Gamma' = 0.25(p_1 - p_3); \quad \Gamma'' = 0.25(p_1 - 2p_2 + p_3). \quad (4)$$

It is interesting to note that the first expression of (4) is proportional to the first difference and the second expression is proportional to the second difference of normalized detector output values. Influence of frequency inaccuracy setting was studied by numerical simulation for deviation of  $\lambda_g$  from correct value of  $\lambda_{g0}$ . For absolute value estimation error less than 5%,  $\lambda_g$  must be in range of  $0.97\lambda_g < \lambda_g < 1.03\lambda_g$ . Under the conditions the phase estimation error is less than 6.5 grad.

The set of equation (3) can be solved using Tikhonov's regularization technique thus the set (3) can be transformed to the set:

$$\begin{bmatrix} 4+\alpha & 0\\ 2 & 2+\alpha \end{bmatrix} \begin{bmatrix} \Gamma'\\ \Gamma'' \end{bmatrix} = \begin{bmatrix} p_1-p_2\\ p_1-p_3 \end{bmatrix}.$$
 (5)

The solution of (5) can be written in the form:

$$\Gamma'' = \frac{6p_1 - 2p_2 - 4p_3 - \kappa}{4 - 0.25(20 + \alpha)(4 + \alpha)};$$

$$\kappa = 0.5(20 + \alpha)p_1 + 0.5(20 + \alpha)p_2;$$

$$\Gamma' = 0.25(2p_1 - 2p_2 - (4 + \alpha)\Gamma'').$$

In general form the choice of the parameter  $\alpha$  is provided by the general residue method, which require estimation of norm some operators and noise level. From practical point of view it is more convenient to carry out measurements with a load with accurate known value of the reflection coefficient, to determine the most accurate value of  $\Gamma$  varying the value of  $\alpha$ . The value of  $\alpha$  provided the most accurate value of  $\Gamma$  one will use as the optimal value assuming the noise level is the same in all measurements.

As a load with accurate known value of the reflection coefficient a short-circuited sliding piston was used. The information about accuracy of estimation was extracted from the accuracy of piston position estimation. The accuracy of piston position set according nonius was  $\pm 0.01$  mm. The range of piston position was from 0 to 35 mm. The average values of position estimation error were 0.105 mm without regularization and 0.073 under condition of  $\alpha = 0.175$  that was the minimal value if  $\alpha$  was varied in range from 0 to 0.4.

Really measured reflection coefficient is the result of reflection of the antenna and inserted reflection coefficient of the object. Thus it is necessary to measure the reflection from antenna and subtract it from data obtained for object under investigation.

After subtraction the phase  $\varphi$  of obtained reflection coefficient  $\Gamma = |\Gamma| \exp(j\varphi)$  is directly proportional to distance to object under consideration that allows one to estimate the distance.

# 3. CALIBRATION PROCEDURE ON BASE OF NEURAL NETWORK

For purposes of calibration the mathematical model of a three-layered neural network with a feedback was constructed [1]. The first layer had 1 neuron that was determined by single input sample of a diode detector for a concrete position x of the probe in a slotted measuring line. The third layer had 1 neuron, that corresponded output value of normalized quantity  $100\sin^2(2\pi x/\lambda_g)$ , where  $\lambda_g$  is wave-length in the waveguide of the slotted measuring line. The first and second layers (input and hidden) neural network had sigmoid function (S - function) activation of neurons; the third (output) layer had the linear one.

Series of neural network mathematical model training with application of a number of algorithms (Levenberg-Marquardt, conjugate gradients, Fletcher-Reeves algorithm, classic algorithm of back propagation, algorithm of back propagation of error with usage secants method, algorithm of scalable conjugate gradients, Polak - Ribiere algorithm) and different number of neurons in the hidden layer (from 2 up to 12 with the step of 1, and from 10 up to 80 with the step of 10) were carried out. It is necessary to mark, that for each selected number of neurons in the hidden layer not less 3 attempts of choosing of weights were attempted. The efficiency of the formed network was checked up by giving of the set of input data.

# The model of the neural network with 4 neurons in the hidden layer has shown the best and stable results, the algorithm of scalable conjugate gradients was used. It is necessary to mark, that the number of neurons in the hidden layer exceeded estimated values. The linear model of a neural network has not shown good results, despite of obvious linear nature of relation between the input data and the target vector of the normalized data. The accuracy of training was $10^{-4}$ .

# 4. EXPERIMENTAL RESULTS

As antenna a pyramidal horn of the length of 200 mm with aperture size of 95×95 mm was used. A waveguide with cross-section of 23×10 mm was used. Operating frequency was 10 GHz. The object was a metal sheet with size of 250×300 mm. The set of distances between of the aperture and the object was 100, 230, 305, 2500 mm. The interval of displacement was 150 mm. The step of displacement was 3 mm. The set of radiuses of curvature was 400, 350, 300, 250, 200, 150 and 100 mm. Measurements were carried out for two orientation of the object: convex side and concave side to the antenna. For convex surface the absolute value of reflection coefficient has typical oscillation behavior but the slope of the dependence is different for different curvatures. Thus the information about the radius of curvatures can be extract from the angle of slope. With decreasing of the radius of curvature, the value of reflection coefficient is decreasing too. The phase contains information about the displacement. For distances of 305-455 mm the range of displacement was approximately 195 mm instead of 150 mm thus using the factor of 1.302 - 1.315 we can obtain the correct value. The application of regularization allowed us to diminish the average error from 0.30 to 0.28 mm and from 1.50 to 1.27 mm for maximal value of the error. The same behavior has been observed for orientation of concave side to the antenna. The factor was 1.297 -1.317 that allows us to suppose the factor is the same for both situations. The application of regularization allowed us to diminish the average error from 0.38 to 0.31 mm and from 1.57 to 1.26 mm for maximal value of the error.

Application of Fresnel lens allowed us to obtain the signal in 4 dB greater than without the lens and diminish the average error in 1.3 times. It is interesting to note the error has not positive trend as for situation without the lens.

#### 5. CONCLUSION

The experimental data has showed the calibration by means of neural networks has allowed one to obtain more correct estimations of reflection coefficient. Integrally, processing method which is conventional in holography with three reference signals has provided rather accurate estimations of complex reflection coefficient as near to unity so near to zero. The application of regularization provided possibility to obtain more accurate results. Application of Fresnel lens allowed us to obtain the signal in 4 dB greater than without the lens and diminish the average error in 1.3 times and to carry out measurements up to 2.5 m.

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