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INTERPROBE DISTANCE ERROR COMPENSATION IN PROBE MEASUREMENTS OF MECHANICAL DISPLACEMENT

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Зондові вимірювання переміщення механічних об’єктів є вельми привабливими з точки зору простоти апаратної реалізації. На цей час загальновживаною міжзондовою відстанню є одна восьма довжини хвилі електромагнітного випромінювання у хвилеводі. Практична реалізація цієї міжзондової відстані з високим ступенем точності може бути складною задачею, особливо в міліметровому діапазоні довжин хвиль. Однак у літературі також відомі методи, що використовують довільну міжзондову відстань. Тому задачу можна звести до визначення фактичної міжзондової відстані. У цій статті пропонується простий метод визначення фактичної міжзондової відстані за допомогою електричних вимірювань з використанням короткозамикального толока. У цьому методі міжзондова відстань знаходиться зі струмів напівпровідникових детекторів, з’єднаних із зондами. Спочатку короткозамикальний толок установлюється так, щоб струм зонда, дальшого від толока (дальнього зонда) досягав максимуму, і вимірюється струм зонда, ближчого до толока (ближнього зонда). Потім короткозамикальний толок відводиться далі від зондів, доки струм дальнього зонда не стане рівним півсумі його максимального й мінімального значень, і знову вимірюється струм ближнього зонда. З цих вимірювань знаходяться тригонометричні функції, до аргументу яких входить відношення міжзондової відстані до довжини хвилі електромагнітного випромінювання у хвилеводі. Міжзондову відстань можна однозначно визначити з цих тригонометричних функцій за умови, що точність установки міжзондової відстані не виходить за межі однієї четвертої довжини хвилі електромагнітного випромінювання у хвилеводі, що звичайно має місце на практиці. Метод може бути використаним при виготовленні мікрохвильових датчиків переміщення.

Ключові слова: *комплексний коефіцієнт відбиття, переміщення, електричний зонд, мікрохвильова інтерферометрія, напівпровідниковий детектор.*

Probe measurements of the displacement of mechanical objects by microwave interferometry are highly attractive in terms of hardware implementation simplicity. At present, the commonly used interprobe distance is one eighth of the guided operating wavelength. Implementing this interprobe distance with a high degree of accuracy may be a challenge, especially in the millimeter-wave band. However, probe methods that use an arbitrary interprobe distance are reported in the literature too. Because of this, the problem may be reduced to determining the actual interprobe distance. This paper presents a simple method for the determination of the actual interprobe distance by electrical measurements with the use of a short-circuiting piston. In this method, the interprobe distance is extracted from the currents of the semiconductor detectors connected to the probes. First, the short-circuiting piston is positioned so that the current of the probe that is farther from piston (the far probe) is a maximum, and the current of the probe that is closer to the piston (the near probe) is measured. Then the short-circuiting piston is moved away from the probes until the current of the far probe becomes equal to the half-sum of its maximum and minimum values, and the current of the near probe is measured again. From these measurements, trigonometric functions whose argument includes the ratio of the interprobe distance to the guided operating wavelength are found. The interprobe distance can be determined unambiguously from these trigonometric functions provided that the interprobe distance accuracy is within one fourth of the guided operating wavelength, which is usually met in actual practice. The method may be used in the manufacturing of microwave displacement sensors.

Keywords: *complex reflection coefficient, displacement, electrical probe, interprobe distance, microwave interferometry, semiconductor detector.*

Microwave measurements are widely used in the determination of various parameters such as distance, displacement, speed, dielectric permittivity, etc. In particular, microwave interferometry is an ideal means in terms of the development of motion sensors [1]. This is due to its ability to provide fast noncontact measurements and its applicability to dusty or smoky environments (as distinct from laser Doppler sensors [2–4] or vision-based systems using digital image processing techniques [5]). An important advantage over radar methods (both traditional pulse ones and recently developed continuous-wave step-frequency ones [6, 7]) is its simple hardware implementation. In microwave interferometry, the displacement of the object under measurement (target) is extracted from the phase shift between the signal reflected from the target and the reference signal, i. e., from the phase of the complex reflection coefficient. In terms of hardware implementation simplicity, probe methods are highly attractive [8, 9]. This is due to the fact that in probe methods the phase of the complex reflection coefficient can be extracted from the currents of the semiconductor detectors connected to probes placed in a waveguide section without recourse to special hardware, such as a power divider and a phase-detecting processor [10, 11], a phase-shift modulator and a balanced mixer [12], etc.

At present, the commonly used interprobe distance is one eighth of the guided operating wavelength λ_g. Providing this interprobe distance with a high degree of accuracy may be a challenge, especially in the millimeter-wave band. However, expressions that relate the phase of the complex reflection coefficient to the detector currents in the case of an arbitrary interprobe distance in the neighborhood of $\lambda_g/8$ are reported in the literature too [13, 14]. Because of this, the problem may be reduced to determining the actual interprobe distance. This paper presents a simple method for the determination of the actual interprobe distance by electrical measurements.

Consider two probes 1 and 2 connected to square-law semiconductor detectors. The probes are placed distance l apart in a waveguide section between a microwave oscillator and a short-circuiting piston, probe 2 being closer to the piston (Fig. 1).

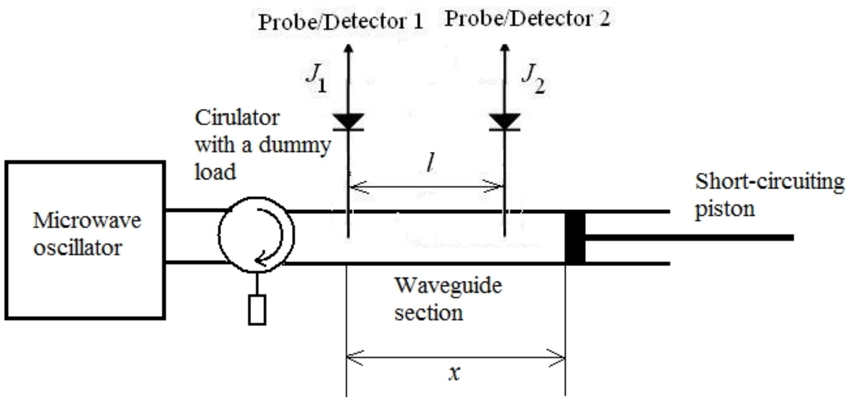

Fig. 1

The detector currents J_1, J_2 normalized to their values in the absence of a reflected wave are expressed in terms of the magnitude R and phase ψ of the complex reflection coefficient at the location of probe 1

$$J_1 = 1 + R^2 + 2R\cos\psi \ , \tag{1}$$

$$J_2 = 1 + R^2 + 2R\cos\left(\psi - \frac{4\pi l}{\lambda_g}\right). \tag{2}$$

The phase ψ is related to the distance x between the probe 1 and the short-circuiting piston as

$$\psi = \frac{4\pi x}{\lambda_g} + \phi$$

where ϕ is the phase shift caused by the reflection.

Let it be desired to find the interprobe distance l from the detector currents J_1 and J_2. The reflection coefficient magnitude R appearing in the expressions for the detector currents can be determined from Eq. (1) as follows. The maximum and minimum values of the current J_1 are attained at $\cos\psi = 1$ and $\cos\psi = -1$, respectively. They are

$$J_{1\max} = 1 + R^2 + 2R = (1+R)^2,$$

$$J_{1\min} = 1 + R^2 - 2R = (1-R)^2.$$

Dividing $J_{1\min}$ by $J_{1\max}$ yields

$$\frac{1-R}{1+R} = \sqrt{\frac{J_{1\min}}{J_{1\max}}}$$

whence

$$R = \frac{1-\sqrt{J_{1\min}/J_{1\max}}}{1-\sqrt{J_{1\min}/J_{1\max}}}. \tag{3}$$

For $\cos\left(\psi - \frac{4\pi l}{\lambda_g}\right)$ appearing in Eq. (2), we have

$$\cos\left(\psi - \frac{4\pi l}{\lambda_g}\right) = \cos\psi\cos\frac{4\pi l}{\lambda_g} + \sin\psi\sin\frac{4\pi l}{\lambda_g}.$$

Hence, Eq. (2) takes the form

$$J_2 = 1 + R^2 + 2R\left(\cos\psi\cos\frac{4\pi l}{\lambda_g} + \sin\psi\sin\frac{4\pi l}{\lambda_g}\right).$$

Let $x_{\max 1}$ be a position of the short-circuiting piston at which $J_1 = J_{1\max}$. Then

$$\cos\psi(x_{\max 1}) = 1,$$

$$\sin\psi(x_{\max 1}) = 0.$$

Because of this,

$$J_2(x_{\max 1}) = 1 + R^2 + 2R\cos\frac{4\pi l}{\lambda_g}$$

whence we get

$$\cos\frac{4\pi l}{\lambda_g} = \frac{J_2(x_{\max 1}) - 1 - R^2}{2R}. \tag{4}$$

Let x_{01} be the first new position of the short-circuiting piston farther from the probes at which $\cos\psi = 0$. From Eq. (1) it follows that this point can be determined as the first point on the right of $x_{\max 1}$ at which

$$J_1(x_{01}) = 1 + R^2.$$

As the short-circuiting piston moves to the right from $x_{\max 1}$, $\cos\psi$ decreases, while $\sin\psi$ increases. Because of this, at $x = x_{01}$ $\sin\psi = 1$, and thus

$$J_2(x_{01}) = 1 + R^2 + 2R\sin\frac{4\pi l}{\lambda_g}$$

whence we get

$$\sin\frac{4\pi l}{\lambda_g} = \frac{J_2(x_{01}) - 1 - R^2}{2R}. \tag{5}$$

From Eqs. (4) and (5) it follows:

$$\frac{4\pi l}{\lambda_g} \equiv \psi_l = \varphi + 2\pi n, \quad n = 0, \pm 1, \pm 2, ..., \tag{6}$$

where the wrapped phase φ is

$$\varphi = \begin{cases} \arctan\dfrac{\sin\psi_l}{\cos\psi_l}, & \sin\psi_l \geq 0, \cos\psi_l \geq 0, \\ \arctan\dfrac{\sin\psi_l}{\cos\psi_l} + \pi, & \cos\psi_l < 0, \\ \arctan\dfrac{\sin\psi_l}{\cos\psi_l} + 2\pi, & \sin\psi_l < 0, \cos\psi_l \geq 0. \end{cases} \tag{7}$$

Let l_0 be the setting value of the interprobe distance and Δl be the setting accuracy. Then

$$l_0 - \Delta l \leq l \leq l_0 + \Delta l,$$

and thus

$$\frac{4\pi(l_0 - \Delta l)}{\lambda_g} \leq \varphi + 2\pi n \leq \frac{4\pi(l_0 + \Delta l)}{\lambda_g}. \tag{8}$$

From Eq. (8) it follows that the integer n satisfies the condition

$$a_{\min} \equiv \frac{2(l_0 - \Delta l)}{\lambda_g} - \frac{\varphi}{2\pi} \leq n \leq \frac{2(l_0 + \Delta l)}{\lambda_g} - \frac{\varphi}{2\pi} \equiv a_{\max}. \tag{9}$$

The integer n is determined from Eq. (9) unambiguously if the following condition is met

$$a_{\max} - a_{\min} = \frac{4\Delta l}{\lambda_g} < 1.$$

Thus, for the integer n to be determined unambiguously from the detector currents, the interprobe distance setting accuracy must not exceed a quarter of the guided operating wavelength. This condition is usually satisfied because the commonly used interprobe distance is one eighth of the guided wavelength.

Given the integer n, the refined interprove distance l is found from Eq. (6) as

$$l = \frac{\lambda_g}{4\pi}(\varphi + 2\pi n). \tag{10}$$

Hence the interprobe distance l may be found by the following algorithm.

1. Moving the short-circuiting piston, determine the minimum detector current J_{1min} and the maximum detector current J_{1max}.

2. Find the reflection coefficient magnitude R by Eq. (3).

3. Position the short-circuiting piston so that the current J_1 is a maximum and measure the current J_2.

4. Find $\cos 4\pi l/\lambda_g$ from Eq. (4).

5. Move the short-circuiting piston away from the probes until the current J_1 becomes equal to $1+R^2$, or to half-sum of J_{1min} and J_{1max}, and measure the current J_2.

6. Find $\sin 4\pi l/\lambda_g$ from Eq. (5).

7. Find the wrapped phase φ from Eq. (7).

8. Find the integer n such that the condition of (9) is satisfied.

9. Find the interprobe distance from Eq. (10).

If displacement measurements are to be conducted at the same wavelength at which the interprobe distance is determined, Steps 7 to 9 may be omitted because the interprobe distance appears in the expressions for the complex reflection coefficient as $\sin 4\pi l/\lambda_g$ and $\cos 4\pi l/\lambda_g$.

Fig. 2 shows the detector currents J_1 and J_2 versus the ratio x/λ_g calculated at $l/\lambda_g = 0.1$, $R = 0.95$, and $\phi = \pi$. The currents were calculated with the addition of a noise component:

$$J_1 = \left(1 + R^2 + 2R\cos\psi\right)(1 + A_n r), \tag{11}$$

$$J_2 = \left[1 + R^2 + 2R\cos\left(\psi - \frac{4\pi l}{\lambda_g}\right)\right]\left(1 + A_n r\right) \tag{12}$$

where A_n is the noise amplitude, and r is a random variable uniformly distributed between –1 and 1. The noise amplitude was put equal to 0.01.

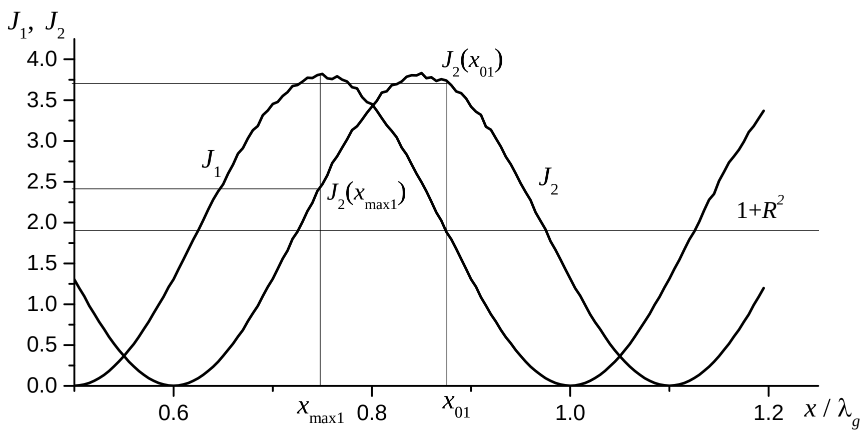

Fig. 2

The ratio l/λ_g found from the data in Fig. 2 is 0.1008, which is in close agreement with its actual value (0.1).

Calculations were conducted to estimate the effect of the interprobe distance accuracy on the accuracy of displacement determination by the two-probe technique reported in [15]. In the calculations, use was made of the actual reflection coefficient magnitude measured in an experiment [16]. In the experiment, the displacement of a brass disc of diameter 126 mm put into motion by a crank mechanism was measured at a free-space operating wavelength of 3 cm, the disc double amplitude was 10 cm, the minimum distance to the antenna was 15 cm, and the interprobe distance was $\lambda_g/8$. Fig. 3 shows this reflection coefficient magnitude as a function of the disc displacement Δx from the position closest to the antenna. The oscillations observed in the figure are due to multiple reflections between the antenna and the target.

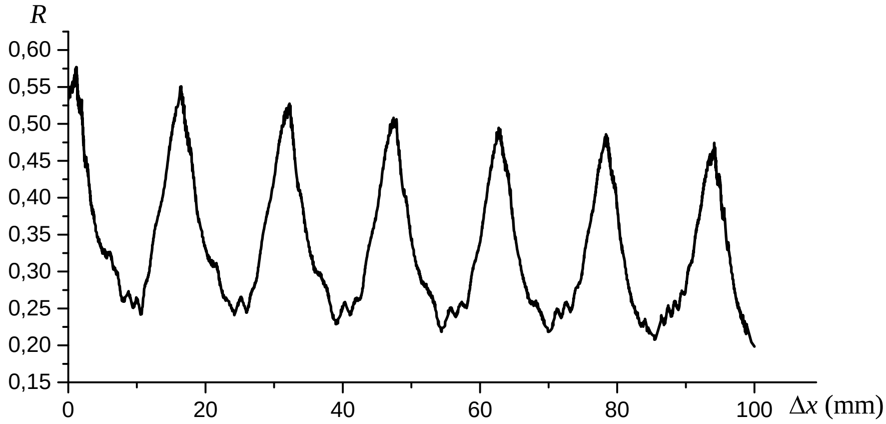

Fig. 3

The time dependence of the target displacement was simulated as

$$\Delta x = A \sin\left(\frac{2\pi t}{T} - \frac{\pi}{2}\right) + A$$

where t is the time and A and T are the target oscillation amplitude and the target oscillation period, which were put equal to 5 cm and 0.5 sec, respectively.

The detector currents were simulated by Eqs. (11) and (12) with a noise amplitude A_n equal to 0.05. The free-space operating wavelength was put equal to 3 cm. The setting value of the interprobe distance was $\lambda_g/8$, its actual value was $\lambda_g/10$, and its refined value was $0.1008\lambda_g$.

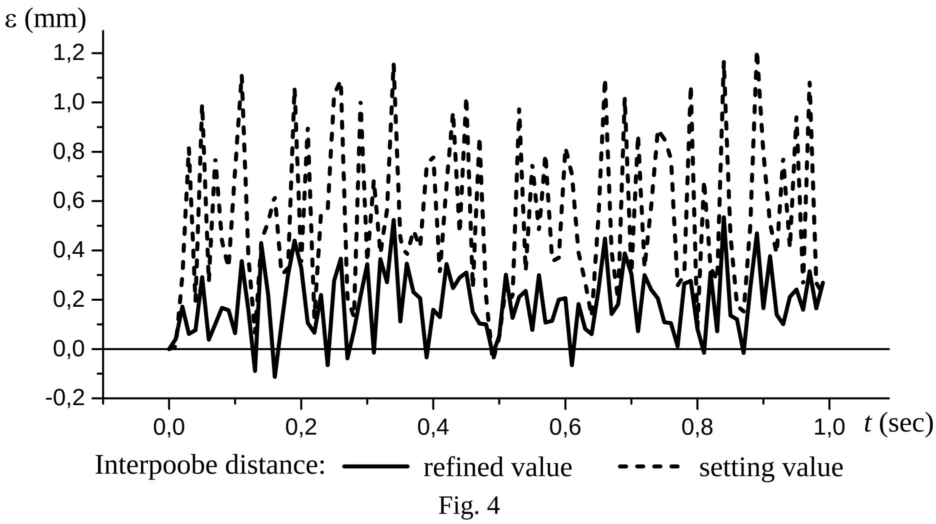

Fig. 4

Fig. 4 shows the displacement error ε in the case where the displacement is determined using the setting value of the interprobe distance ($\lambda_g/8$) and its refined value ($0.1008\lambda_g$) , while its actual value is $\lambda_g/10$. As can be seen from the figure, the use of the refined value of the interprobe distance offers a significant reduction in the displacement error.

The proposed method may be used in the manufacturing of microwave displacement sensors.

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