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TWO-PROBE MEASUREMENTS OF THE DISPLACEMENT OF AN OBJECT WITH ACCOUNT FOR THE ANTENNA REFLECTION COEFFICIENT

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У цій статті розглядається проблема вимірювання переміщення за допомогою надвисокочастотної інтерферометрії при невідомому коефіцієнті відбуття об'єкта у випадку, коли цей коефіцієнт відбиття є порівняним з коефіцієнтом відбиття антени. Мета цієї статті полягає в тому, щоб запропонувати двозондовий метод вимірювання переміщення, що враховує коефіцієнт відбиття антени. Ця мета досягається використанням виразів для квадратурних сигналів і рівняння відносно невідомого модуля коефіцієнта відбиття об'єкта, записаних для випадку відмінного від нуля коефіцієнта відбиття антени. Невідомий модуль коефіцієнта відбиття об'єкта прийнято рівним меншому додатному кореню цього рівняння. Якщо модуль коефіцієнта відбиття об'єкта менший від деякої критичної величини, що залежить від коефіцієнта відбиття антени, то теоретично переміщення визначається точно; у протилежному випадку похибка визначення переміщення не перевищує декількох відсотків від довжини хвилі зондуючого електромагнітного випромінювання у вільному просторі. У залежності від фази коефіцієнта відбиття антени похибка може бути більшою або меншою, ніж у відсутності відбиття від антени, коли максимально можлива похибка складає близько 4,4 % від довжини хвилі зондуючого електромагнітного випромінювання у вільному просторі. Для перевірки запропонованого методу було проведено моделювання визначення переміщення об'єкта, що здійснює гармонічні коливання. При цьому відхилення струмів детекторів від їхніх теоретичних значень моделювалося випадковим струмовим шумом. Результати моделювання показують, що неурахування коефіцієнта відбиття антени у випадку, коли він є порівняним з коефіцієнтом відбиття об'єкта, може призвести до появи значної похибки. Запропонований у цій статті двозондовий метод вимірювання переміщення може бути використаним при розробці мікрохвильових датчиків переміщення.

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

В данной статье рассматривается проблема измерения перемещения с помощью сверхвысокочастотной интерферометрии при неизвестном коэффициенте отражения объекта в случае, когда этот коэффициент отражения сравним с коэффициентом отражения антенны. Цель данной статьи заключается в том, чтобы предложить двухзондовый метод измерения перемещения, учитывающий коэффициент отражения антенны. Эта цель достигается использованием выражений для квадратурных сигналов и уравнения относительно неизвестного модуля коэффициента отражения объекта, записанных для случая отличного от нуля коэффициента отражения антенны. Неизвестный модуль коэффициента отражения объекта принят равным меньшему положительному корню этого уравнения. Если модуль коэффициента отражения объекта меньше некоторой критической величины, зависящей от коэффициента отражения антенны, то теоретически перемещение объекта определяется точно; в противном случае ошибка определения перемещения не превышает нескольких процентов от длины волны зондирующего электромагнитного излучения в свободном пространстве. В зависимости от фазы коэффициента отражения антенны ошибка может быть больше или меньше, чем в случае отсутствия отражения от антенны, когда максимально возможная ошибка составляет около 4,4 % от длины волны зондирующего электромагнитного излучения в свободном пространстве. Для проверки предложенного метода было проведено моделирование определения относительного перемещения объекта, совершающего гармонические колебания. Про этом отклонения токов детекторов от их теоретических значений моделировались случайным токовым шумом. Результаты моделирования показывают, что неучет коэффициента отражения антенны в случае, когда он сравним с коэффициентом отражения объекта, может привести к появлению значительной ошибки. Предложенный в данной статье двухзондовый метод измерения перемещения может быть использован при разработке микроволновых датчиков перемещения.

Ключевые слова: *комплексный коэффициент отражения, перемещение, электрический зонд, микроволновая интерферометрия, полупроводниковый детектор, волноводная секция.*

This paper addresses the problem of displacement measurement by microwave interferometry at an unknown target reflection coefficient in the case where that reflection coefficient is comparable with the reflection coefficient of the antenna. The aim of this paper is to propose a two-probe displacement measurement method that would account for the antenna reflection coefficient. This aim is achieved by using expressions for the quadrature signals and an equation in the unknown magnitude of the target reflection coefficient written for the case of a nonzero antenna reflection coefficient. The unknown magnitude of the target reflection coefficient is taken to be equal to the smaller positive root of that equation. If the magnitude of the target reflection coefficient is smaller than a critical value, which depends on the antenna reflection coefficient, then, theoretically, the target displacement is determined exactly; otherwise, the displacement determination error does not exceed several percent of the free-space operating wavelength. Depending on the phase of the antenna reflection coefficient, the error may be greater or smaller than in the case of a zero antenna reflection coefficient where the worst-case error is about 4.4 % of the free-space operating wavelength. To verify the proposed method, the determination of the relative displacement of a target executing a harmonic vibratory motion was simulated. In doing so, variations of the detector currents from their theoretical values were modeled by random current noise. The simulation results show that ignoring the reflection coefficient of the antenna when it is comparable with that of the target may introduce a sizeable error. The two-probe displacement measurement method proposed in this paper may be used in the development of microwave displacement sensors.

Keywords: *complex reflection coefficient, displacement, electrical probe, microwave interferometry, semiconductor detector, waveguide section.*

Microwave interferometry is an ideal means for motion sensing in various engineering applications [1]. In terms of implementation simplicity, its probe version is especially attractive because it does not require such special devices as, for example, an analog [2] or a digital [3] quadrature mixer. In probe measurements, information on the distance to the target is contained in the phase of the target reflection coefficient. At least three probes are needed for the unknown reflection coefficient to be determined unambiguously [4 – 6]. However, a two-probe displacement determination measurement method was proposed in [7] and verified by experiment in [8]. The method relies on the fact that for two probes the bias error in displacement determination is only introduced for target reflection coefficient magnitudes greater than $2^{-1/2}$ and does not exceed 4.4 % of the free-space operating wavelength in the general case [7]. The method assumes that there is no reflection from the antenna, i. e. the only reflected wave that propagates in the waveguide section is the wave reflected from the target. However, this assumption obviously ceases to be true in the case where target and the antenna reflection coefficients are comparable. This paper presents a two-probe displacement measurement method that accounts for the antenna reflection coefficient.

Consider two probes, 1 and 2, with square-law semiconductor detectors placed one eighth of the guided operating wavelength λ_g apart in a waveguide section between a microwave oscillator and a target so that probe 1 is farther from the target (Fig. 1).

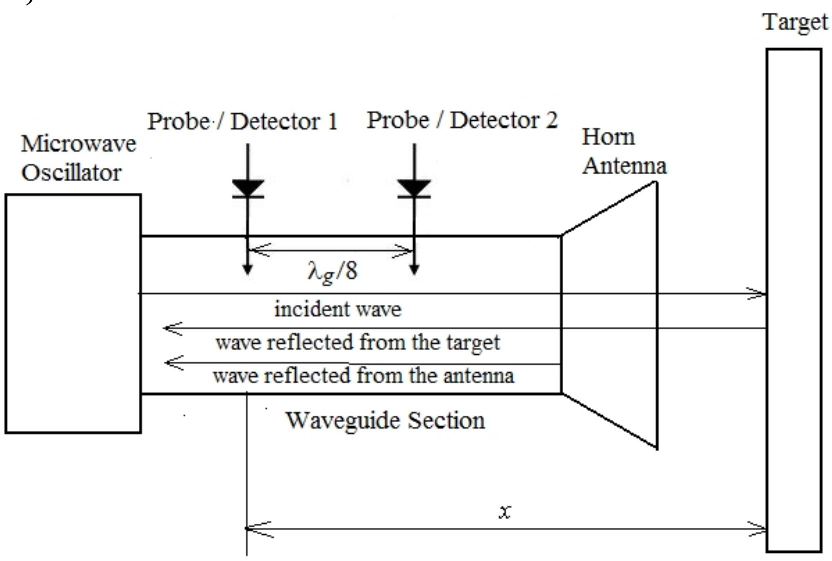

Fig. 1

The waveguide section has a horn antenna at its end, which emits the electromagnetic wave generated by the microwave oscillator (the incident wave) and receives the wave reflected from the target. Before the incident wave reaches the target and is reflected therefrom, part of it will be reflected from the horn antenna. Because of this, three electromagnetic waves will interfere with one another in the waveguide section: the incident wave, the wave reflected from the target, and the wave reflected from the antenna.

Information on the distance x between the target and probe 1 is contained in the phase of the complex reflection coefficient of the target, which may be represented as follows [9, 10]

$$\psi = \frac{4\pi x}{\lambda_0} + \phi$$

where λ_0 is the free-space operating wavelength and ϕ is the phase component that is governed by the waveguide section and horn antenna geometry and the phase shift caused by the reflection and does not depend on the distance x.

The displacement Δx of the target at time t relative to its initial position $x(t_0)$ can be unambiguously determined from the quadrature signals $\sin\psi$ and $\cos\psi$ using the following phase unwrapping algorithm [11]

$$\varphi(t_n) = \begin{cases} \arctan\dfrac{\sin\psi(t_n)}{\cos\psi(t_n)}, & \sin\psi(t_n) \ge 0, \cos\psi(t_n) \ge 0, \\ \arctan\dfrac{\sin\psi(t_n)}{\cos\psi(t_n)} + \pi, & \cos\psi(t_n) < 0\,, \\ \arctan\dfrac{\sin\psi(t_n)}{\cos\psi(t_n)} + 2\pi, & \sin\psi(t_n) < 0, \cos\psi(t_n) \ge 0, \end{cases} \tag{1}$$

$$\Delta\varphi(t_n) = \varphi(t_n) - \varphi(t_{n-1})\,, \tag{2}$$

$$\theta(t_n) = \begin{cases} 0, \ n = 0, \\ \theta(t_{n-1}) + \Delta\varphi(t_n), \quad |\Delta\varphi(t_n)| \le \pi, \quad n = 1, 2, \ldots, \\ \theta(t_{n-1}) + \Delta\varphi(t_n) - 2\pi\,\mathrm{sgn}[\Delta\varphi(t_n)], \ |\Delta\varphi(t_n)| > \pi, \ n = 1, 2, .., \end{cases} \tag{3}$$

$$\Delta x(t_n) = \frac{\lambda_0}{4\pi}\theta(t_n)\,, \quad n = 0, 1, 2, \ldots, \tag{4}$$

where φ and θ are the wrapped and the unwrapped phase, respectively.

In the assumption of harmonic vibration of the target, for this algorithm to be applicable the sampling frequency of the detector currents must be no lower than $8\pi A_{\max} f_{\max}/\lambda_0$ where $A_{\max}$ and $f_{\max}$ are the target vibration maximum amplitude and frequency, respectively [7].

In the case of a nonzero antenna reflection coefficient, the quadrature signals are given by the following expressions [12]:

$$\sin\psi = \frac{A_2 - R^2}{2RB} \tag{5}$$

$$\cos\psi = \frac{A_1 - R^2}{2RB}$$

$$A_1 = a + bR_a \sin\psi_a,\ A_2 = a - b(1 + R_a \cos\psi_a), \tag{6}$$

$$B = 1 + \sqrt{2}R_a \sin\left(\psi_a + \frac{\pi}{4}\right) \tag{7}$$

$$a = J_1 - 1 - 2R_a \cos\psi_a - R_a^2, \quad b = J_1 - J_2 - 2R_a(\cos\psi_a - \sin\psi_a)$$

where J_1 and J_2 are the current of the detector connected to probe 1 and the current of the detector connected to probe 2 normalized to their values in the absence of reflected waves (these values have to be determined prior to displacement measurements, for example, using a matched load at the end of the waveguide section), R_a and ψ_a are the magnitude and the phase of the antenna reflection coefficient, and R is the magnitude of the target reflection coefficient. For non-square-law detectors, Eqs. (5) and (6) will remain valid if J_1 and J_2 are replaced with $|E_1/E_{in}|^2$ and $|E_2/E_{in}|^2$, respectively, where E_1 is the resulting electric filed amplitude at the location of probe 1, E_2 is the resulting electric filed amplitude at the location of probe 2, and E_{in} is the incident wave amplitude. The ratios $|E_1/E_{in}|$ and $|E_2/E_{in}|$ can be determined from the detector currents and the detector calibration curves.

As shown in [12], R_a, $\sin\psi_a$, and $\cos\psi_a$ can be determined as follows:

$$R_a = \left[\frac{J_{10} + J_{20}}{2} - \sqrt{\frac{(J_{10} + J_{20})^2}{4} - \frac{(J_{10} - 1)^2 + (J_{20} - 1)^2}{2}}\right]^{1/2},$$

$$\cos\psi_a = \frac{J_{10} - 1 - R_a^2}{2R_a}, \quad \sin\psi_a = \frac{J_{20} - 1 - R_a^2}{2R_a}$$

where J_{10} and J_{20} are the currents J_1 and J_2 at $R = 0$, i. e., in the case where the only reflected wave in the waveguide section is the wave reflected from the horn antenna. Technically, the case $R = 0$ may be implemented, for example, with the horn antenna operating into a matched load.

The unknown magnitude R of the target reflection coefficient satisfies the following equation [12]:

$$R^4 - R^2(2B^2 + A_1 + A_2) + \frac{A_1^2 + A_2^2}{2} = 0. \tag{8}$$

This biquadratic equation has two positive roots

$$R_1 = \left[B^2 + \frac{A_1 + A_2}{2} + \sqrt{\left(B^2 + \frac{A_1 + A_2}{2}\right)^2 - \frac{A_1^2 + A_2^2}{2}}\right]^{1/2},$$

$$R_2 = \left[B^2 + \frac{A_1 + A_2}{2} - \sqrt{\left(B^2 + \frac{A_1 + A_2}{2} \right)^2 - \frac{A_1^2 + A_2^2}{2}} \right]^{1/2}.$$

One of these roots is obviously extraneous. To identify the extraneous positive root, let us express the absolute term of Eq. (8) in terms of *R* and ψ using Eqs. (5) and (6)

$$\frac{A_1^2 + A_2^2}{2} = R^2 \left[R^2 + 2\sqrt{2} BR \sin\left(\psi + \frac{\pi}{4} \right) + 2B^2 \right]. \qquad (9)$$

On the one hand, the square root of the absolute term of a biquadratic equation with real roots is equal to the product of its positive roots; on the other hand, *R* is a positive root of the biquadratic equation of (8). Because of this, it follows from Eq. (9) that the other positive root of Eq. (8), which is its extraneous positive root, is

$$R_{ext} = \left[R^2 + 2\sqrt{2} BR \sin\left(\psi + \frac{\pi}{4} \right) + 2B^2 \right]^{1/2}.$$

The extraneous root will be greater than or equal to *R* if

$$\sin\left(\psi + \frac{\pi}{4} \right) \geq -\frac{B}{\sqrt{2} R}.$$

This condition will always be satisfied if $B/(\sqrt{2}R) \geq 1$, i. e. $R \leq B/\sqrt{2}$. Because of this, for $R \leq B/\sqrt{2}$ the magnitude *R* of the target reflection coefficient will be given by the smaller positive root R_2 at any value of ψ. With a knowledge of *R*, the quadrature signals sinψ and cosψ appearing in Eq. (1) can be determined from Eqs. (5) and (6).

In the case $B/(\sqrt{2}R) < 1$, i. e. $R > B/\sqrt{2}$, the root R_2 will not always be equal to R. However, as will be shown below, in this case the displacement can also be determined to reasonable accuracy if the root R_2 is taken as the reflection coefficient magnitude. The root R_2 will be extraneous when

$$\sin\left(\psi + \frac{\pi}{4} \right) < -\frac{B}{\sqrt{2} R},$$

or, in terms of the wrapped phase,

$$\varphi_l = \frac{3\pi}{4} + \arcsin \frac{B}{\sqrt{2} R} < \varphi < \frac{7\pi}{4} - \arcsin \frac{B}{\sqrt{2} R} = \varphi_r.$$

If the root R_2 is taken as the reflection coefficient magnitude when it is extraneous, then the expressions of (5) and (6) for sinψ and cosψ will give their apparent values $\sin\psi_{ap}$ and $\cos\psi_{ap}$

$$\sin \psi_{ap} = \frac{A_2 - R_{ext}^2}{2 R_{ext} B} = -\frac{R \cos \psi + B}{R_{ext}}$$

$$\cos\psi_{ap} = \frac{A_1 - R_{ext}^2}{2R_{ext}B} = -\frac{R\sin\psi + B}{R_{ext}},$$

which, in their turn, on substitution into Eq. (1) will give the apparent wrapped phase φ_{ap} (here, it is accounted for the fact that $\cos\psi = \cos\varphi$ and $\sin\psi = \sin\varphi$)

$$\varphi_{ap} = \begin{cases} \arctan\dfrac{F_1}{F_2}, & F_1 \geq 0,\ F_2 \geq 0, \\ \arctan\dfrac{F_1}{F_2} + \pi, & F_2 < 0, \\ \arctan\dfrac{F_1}{F_2} + 2\pi, & F_1 < 0,\ F_2 > 0, \end{cases} \tag{10}$$

$$F_1 = -(R\cos\psi + B) = -(R\cos\varphi + B), \tag{11}$$

$$F_2 = -(R\sin\psi + B) = -(R\sin\varphi + B). \tag{12}$$

The phase error $\Delta\varphi_{er}$ introduced when the root R_2 is taken as the reflection coefficient magnitude in the case where this root is extraneous will be

$$\Delta\varphi_{er} = \varphi_{ap} - \varphi.$$

Since at $\varphi = \varphi_l$ and $\varphi = \varphi_r$ the apparent wrapped phase coincides with the actual one, $\Delta\varphi_{er}(\varphi_l) = \Delta\varphi_{er}(\varphi_r) = 0$. The phase error is also equal to zero at $\varphi = 5\pi/4$. This can be demonstrated as follows. Since the magnitude R_a of the antenna reflection coefficient usually does not exceed 0.1, it follows from Eq. (7) that B lies between $1 - 0.1\sqrt{2} = 0.8586$ and $1 + 0.1\sqrt{2} = 1.1414$. Since $R \leq 1$, it follows from Eqs. (10) to (12) that $F_1(\varphi = 5\pi/4) = F_2(\varphi = 5\pi/4) < 0$, and thus $\varphi_{ap}(\varphi = 5\pi/4) = 5\pi/4$.

For the derivative of $\Delta\varphi_{er}$ with respect to φ, we have

$$\frac{\partial\Delta\varphi_{er}}{\partial\varphi} = -\frac{2R^2 + 3\sqrt{2}BR\sin\left(\varphi + \dfrac{\pi}{4}\right) + 2B^2}{(R\cos\varphi + B)^2 + (R\sin\varphi + B)^2}. \tag{13}$$

Between $\varphi_l = 3\pi/4 + \arcsin(B/\sqrt{2}R)$ and $\varphi_r = 7\pi/4 - \arcsin(B/\sqrt{2}R)$, this derivative has zeros at the points

$$\varphi_1 = \frac{3\pi}{4} + \arcsin\frac{\sqrt{2}(R^2 + B^2)}{3BR},$$

$$\varphi_2 = \frac{7\pi}{4} - \arcsin\frac{\sqrt{2}(R^2 + B^2)}{3BR},$$

is positive on the interval (φ_1, φ_2) and is negative on the intervals $[\varphi_l, \varphi_1)$ and $(\varphi_2, \varphi_r]$, Because of this, the function $\Delta\varphi_{er}(\varphi)$ has a negative minimum at $\varphi = \varphi_1$ and a positive maximum at $\varphi = \varphi_2$.

In the variable $\alpha = \varphi - 5\pi/4$, Eq. (13) becomes

$$\frac{\partial \Delta\varphi_{er}}{\partial \alpha} = -\frac{2R^2 + 3\sqrt{2}BR\sin\left(\alpha + \frac{3\pi}{2}\right) + 2B^2}{B^2 + R^2 + BR\sin\left(2\alpha + \frac{\pi}{2}\right)}.$$

This derivative is even in α. Since the function $\Delta\varphi_{er}(\alpha)$ is zero at $\alpha = 0$, it may be represented as

$$\Delta\varphi_{er}(\alpha) = \int_0^{\alpha} \frac{\partial \Delta\varphi_{er}(\alpha')}{\partial \alpha'} d\alpha'.$$

On rearrangements, we have

$$\Delta\varphi_{er}(\alpha) = \int_0^{\alpha} \frac{\partial \Delta\varphi_{er}(\alpha')}{\partial \alpha'} d\alpha' = -\int_0^{-\alpha} \frac{\partial \Delta\varphi_{er}(-\alpha')}{\partial \alpha'} d\alpha' = -\int_0^{-\alpha} \frac{\partial \Delta\varphi_{er}(\alpha')}{\partial \alpha'} d\alpha' = -\Delta\varphi_{er}(-\alpha).$$

So the function $\Delta\varphi_{er}(\alpha)$ is odd, i. e., the function $\Delta\varphi_{er}(\varphi)$ is antisymmetric about the point $\varphi = 5\pi/4$. Since the points $\varphi = \varphi_1$ and $\varphi = \varphi_2$ are symmetric about $\varphi = 5\pi/4$, the negative minimum reached at $\varphi = \varphi_1$ and the positive maximum reached at $\varphi = \varphi_2$ are equal in magnitude. Since $\Delta\varphi_{er}(\varphi_l) = \Delta\varphi_{er}(5\pi/4) = \Delta\varphi_{er}(\varphi_r) = 0$ and $\partial\Delta\varphi_{er}/\partial\varphi$ is positive on the interval (φ_1, φ_2) and negative on the intervals $[\varphi_l, \varphi_1)$ and $(\varphi_2, \varphi_r]$, the function $\Delta\varphi_{er}(\varphi)$ is negative on the interval $(\varphi_l, 5\pi/4)$ and positive on the interval $(5\pi/4, \varphi_r)$.

From Eqs. (1) to (4) it follows that the displacement error is governed only by the phase error at the initial and the current measurement point because the errors at the intermediate points cancel one another. Because of this, at a fixed R the maximum possible error in displacement determination will be

$$\Delta x_{er\,\max} = \frac{\lambda_0}{4\pi}\left[\Delta\varphi_{er}(\varphi_2) - \Delta\varphi_{er}(\varphi_1)\right] = \frac{\lambda_0}{2\pi}\Delta\varphi_{er}(\varphi_2)$$

For the derivative of $\Delta\varphi_{er}$ with respect to R, we have

$$\frac{\partial \Delta\varphi_{er}}{\partial R} = \frac{\sqrt{2}B\sin\left(\varphi + \frac{3\pi}{4}\right)}{(R\cos\varphi + B)^2 + (R\sin\varphi + B)^2}$$

This derivative is negative on the interval $(\varphi_l, 5\pi/4)$ where $\Delta\varphi_{er}$ is negative, and it is positive on the interval $(5\pi/4, \varphi_r)$ where $\Delta\varphi_{er}$ is positive. Because of this, at a fixed φ the phase error increases in magnitude with R, and thus the maximum phase error is attained at $R = 1$.

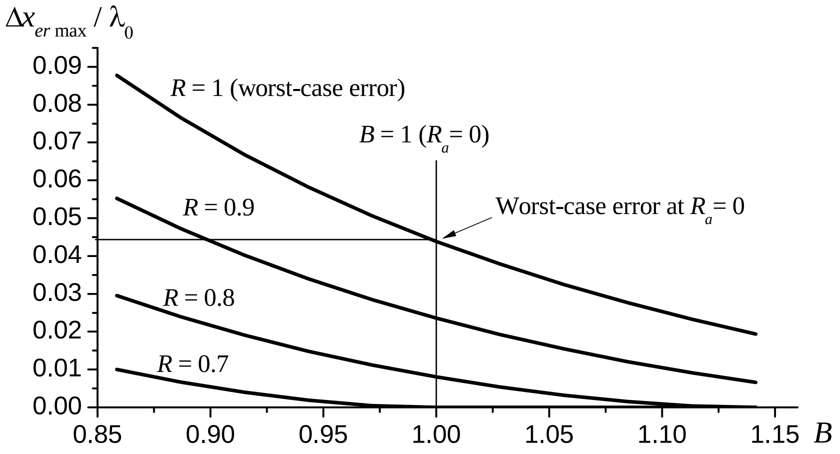

Fig. 2

Fig. 2 shows $\Delta x_{er\,\max}/\lambda_0$ as a function of *B*. As illustrated, in free-space measurements (*R* < 1) the displacement can be determined to a few percent of the operating wavelength if the root R_2 is taken as the magnitude of the target reflection coefficient. It can also be seen from Fig. 2 that the error decreases with *B*. Because of this, at $B > 1$ the error is smaller than in the absence of reflection from the antenna ($B = 0$) provided that the antenna reflection coefficient is accounted for.

To verify the proposed method, the determination of the relative displacement of a target executing a harmonic vibratory motion was simulated. In doing so, variations of the detector currents from their theoretical values were modeled by random current noise. The relative displacement Δx of the target from its initial position was simulated as

$$\Delta x(t) = A \sin(2\pi t/T)$$

and the detector currents J_1 and J_2 were simulated as

$$J_1 = J_{1th}(1 + A_n r), \quad (15)$$

$$J_2 = J_{2th}(1 + A_n r), \quad (16)$$

$$J_{1th} = J_0 + 2R_a \cos\psi_a + 2R\cos\psi,$$

$$J_{2th} = J_0 + 2R_a \sin\psi_a + 2R\sin\psi,$$

$$J_0 = 1 + R_a^2 + R^2 + 2R_a R\cos(\psi - \psi_a), \quad \psi = \psi_0 + \frac{4\pi\Delta x(t)}{\lambda_0}$$

where t is the time, A and T are the target vibration amplitude and period, J_{1th} and J_{2th} are the theoretical values of the detector currents [12], ψ_0 is the phase ψ at $t = 0$, A_n is the noise amplitude, and r is a random variable uniformly distributed between –1 and 1.

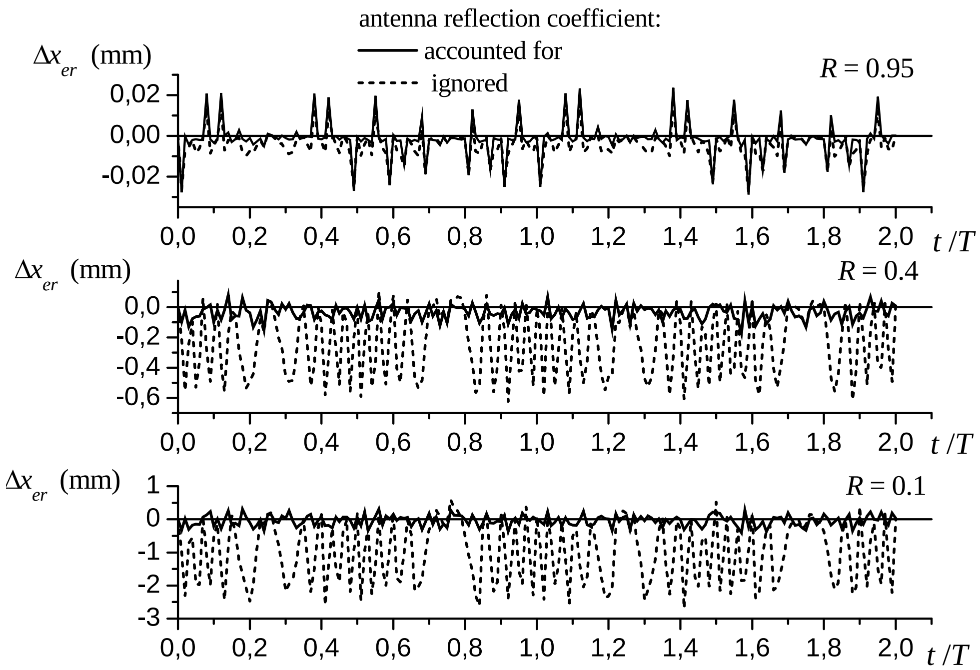

Fig. 3

The calculations were conducted for different values of the target reflection magnitude R at $\lambda_0 = 3$ cm, $A = 2.5\lambda_0$, $\psi_0 = \pi/2$, $R_a = 0.05$, $\psi_a = 5\pi/4$, and $A_n = 0.015$. The target displacement was determined from the detector currents given by Eqs. (15) and (16) with the antenna reflection coefficient both accounted for (the proposed method) and ignored (the method of [7]). Fig. 3 shows the displacement error Δx_{er}, i. e., the difference of the displacement found from the detector currents and the actual displacement given by Eq. (14). As illustrated, when the reflection coefficient of the target is comparable with that of the antenna, ignoring the latter may result in a sizeable error.

The proposed method may be used in the development of microwave displacement sensors, especially in cases where the sensor–target distance is large enough for the target reflection coefficient to be comparable with the antenna one.

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