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EXPERIMENTAL VERIFICATION OF A TWO-PROBE IMPLEMETRATION OF MICROWAVE INTERFEROMETRY FOR DISPLACEMENT MEASUREMENT

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Розглядається задача експериментальної перевірки нещодавно запропонованого двозондового метода вимірювання переміщення на основі надвисокочастотної інтерферометрії. Метою цієї роботи є розробка методики, що дозволяє провести перевірку цього метода шляхом порівняння виміряної й фактичної часової залежності переміщення об'єкта, що рухається, без використання складного обладнання для фотореєстрації. Ця мета досягається тим, що об'єкт приводиться до руху за допомогою кривошипно-шатунного механізму, так що фактичне переміщення об'єкта можна розрахувати за радіусом і довжиною плеча кривошипа, періодом обертання кривошипа та кутом повороту кривошипа у початковий момент часу. Описані в цій роботі експерименти підтвердили працездатність вищевказаного двозондового метода вимірювання переміщення, тим самим підтвердивши, що для вимірювання переміщення при невідомому коефіцієнті відбиття достатньо двох зондів. При довжині хвилі зондуючого електромагнітного випромінювання 3 см, розмасі коливань об'єкта 10 см і 15 см і частоті коливань об'єкта близько 2 Гц цей метод дозволяє визначити миттєве значення переміщення з максимальною похибкою близько 3 мм і середньою похибкою близько 1 мм без будь-якої попередньої обробки даних вимірювань, такої як фільтрація, згладжування тощо. У порівнянні із загальноприйнятими тризондовими вимірюваннями зменшення кількості зондів дозволяє спростити конструкцію й виготовлення хвилевідної секції, а також послабити паразитний ефект перевідбиттів між зондами. Простота апаратної реалізації метода дозволяє використати його при розробці бортових давачів для вимірювання переміщення об'єктів космічного сміття відносно космічного апарата для видалення космічного сміття.

Рассматривается задача экспериментальной проверки недавно предложенного двухзондового метода измерения перемещения на основе сверхвысокочастотной интерферометрии. Целью данной статьи является разработка методики, позволяющей провести проверку этого метода путем сравнения измеренной и фактической временной зависимости перемещения движущегося объекта без использования сложного оборудования для фоторегистрации. Данная цель достигается тем, что объект приводится в движение с помощью кривошипно-шатунного механизма, так что фактическое перемещение объекта можно рассчитать по радиусу и длине плеча кривошипа, периоду вращения кривошипа и углу поворота кривошипа в начальный момент времени. Описанные в данной работе эксперименты подтвердили работоспособность вышеуказанного двухзондового метода измерения перемещения, тем самым подтвердив, что для измерения перемещения при неизвестном коэффициенте отражения достаточно двух зондов. При длине волны зондирующего электромагнитного излучения 3 см, размахе колебаний объекта 10 см и 15 см и частоте колебаний объекта около 2 Гц этот метод позволяет определить мгновенное значение перемещения объекта с максимальной погрешностью около 3 мм и средней погрешностью около 1 мм без какой-либо предварительной обработки данных измерений, такой как фильтрация, сглаживание и т. п. По сравнению с общепринятыми трехзондовыми измерениями уменьшение количества зондов позволяет упросить конструкцию и изготовление волноводной секции и ослабить паразитный эффект переотражений между зондами. Простота аппаратной реализации метода позволяет использовать его при разработке бортовых датчиков для измерения перемещения объектов космического мусора относительно космического аппарата для удаления комического мусора.

This paper addresses the problem of experimental verification of a recently proposed two-probe method for displacement measurement based on microwave interferometry. The aim of this paper is to develop a technique that would allow one to verify that method by comparing the measured displacement vs. time relationship of a moving target with the actual one without recourse to complex photorecording equipment. This aim is achieved by the target being put in motion using a crank mechanism so that the actual target displacement can be calculated from the crank radius and arm length, the crank rotation period, and the crank angle at the initial time. The experiments described in this paper have verified the above-mentioned two-probe displacement measurement method, thus confirming that the displacement can be determined from probe measurements at an unknown reflection coefficient using as few as two probes. At an operating wavelength of 3 cm, a target double amplitude of 10 cm and 15 cm, and a target vibration frequency of about 2 Hz, the method allows one to determine the instantaneous target displacement with a maximum error of about 3 mm and an average error of about 1 mm without any preprocessing of the measured data, such as filtering, smoothing, etc. In comparison with conventional three-probe measurements, the reduction in the number of probes simplifies the design and manufacture of the measuring waveguide section and alleviates the problem of interprobe interference. The simple hardware implementation of the above-mentioned displacement measurement method allows one to use it in the development of motion sensors to measure the displacement of space debris objects onboard a dedicated spacecraft for space debris removal.

Keywords: *complex reflection coefficient, displacement, electrical probe, experimental verification, semiconductor detector, waveguide section.*

Microwave interferometry is an ideal means for displacement measurement in various engineering applications [1]. This is due to its ability to provide fast non-contact measurements, applicability to dusty or smoky environments (as distinct from laser Doppler sensors [2 – 4] or vision-based systems using digital image processing techniques [5]), and 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. Recently, a two-probe displacement measurement method based on microwave interferometry was proposed [6]. In that method, the quadrature signals needed for the determination of the phase shift are extracted from the outputs of two probes placed in a waveguide section one eighth of the guided operating wavelength λ_g apart. In hardware implementation, the method is far simpler than conventional techniques based on quadrature mixing [7, 8], which need special hardware incorporating a power divider and a phase-detecting processor (an analog [7] or a digital [8] quadrature mixer) and face the problem of minimization of the nonlinear phase response of the quadrature mixer arising from its phase and amplitude unbalances. A distinctive feature of the method proposed in [6] is the possibility of displacement measurement at an unknown reflection coefficient with as few as two probes, while since the classic text by Tischer [9] it has been universally believed that at least three probes are needed to determine or eliminate the unknown reflection coefficient. Theoretically, the method gives the exact value of the displacement for reflection coefficients (at the location of the probes) no greater than $1/\sqrt{2}$ and in the general case determines it to a worst-case accuracy of about 4.4 % of the operating wavelength.

In [6], the method was verified by comparing the measured target double amplitude with the actual one. Clearly it is of much more interest to verify the method by comparing the measured displacement vs. time relationship of a moving target with the actual one. The aim of this paper is to develop a technique that would allow one to do this without recourse to complex photorecording equipment.

This aim may be achieved using a target put in motion by a crank mechanism as shown in Fig. 1.

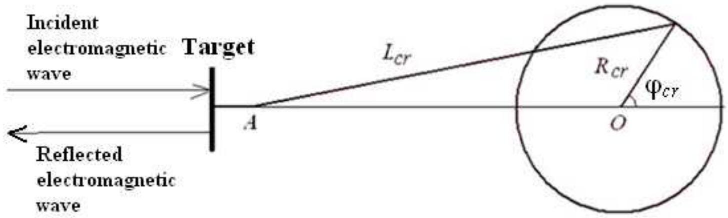

Fig. 1

As can be seen from Fig. 1, the displacement Δx of the target at time t relative to its initial position at $t = 0$ is

$$\Delta x(t) = OA(\varphi_{cr0}) - OA[\varphi_{cr}(t)] \tag{1}$$

$$OA(\varphi_{cr}) = \sqrt{L_{cr}^2 - R_{cr}^2 \sin^2 \varphi_{cr}} - R_{cr} \cos \varphi_{cr}\, , \tag{2}$$

$$\varphi_{cr}(t) = \varphi_{cr0} + \frac{2\pi t}{T} \tag{3}$$

where φ_{cr} is the crank angle, φ_{cr0} is the crank angle at $t = 0$, OA is the distance from the rotation center to the end of the crank arm, L_{cr} is the crank arm length, R_{cr} is the crank radius, and T is the rotation period.

As can be seen from Eqs. (1) to (3), the displacement is a periodical time function with a period equal to T. The derivative of Δx with respect to the time is

$$\frac{d\Delta x}{dt} = \frac{2\pi}{T}\left(\frac{R_{cr}^2 \sin\varphi_{cr} \cos\varphi_{cr}}{\sqrt{L_{cr}^2 - R_{cr}^2 \sin^2 \varphi_{cr}}} - R_{cr} \sin\varphi_{cr} \right) = -\frac{2\pi}{T} \frac{OA \cdot R_{cr} \sin\varphi_{cr}}{\sqrt{L_{cr}^2 - R_{cr}^2 \sin^2 \varphi_{cr}}}. \tag{4}$$

For convenience, define $t' = t + \varphi_{cr0} T/2\pi$. It follows from Eq. (4) that the derivative becomes zero at $t' = nT/2$, $n = 0, \pm 1, \pm 2, \ldots,$ and it changes its sign from positive to negative and from negative to positive at $t' = mT$, $m = 0, \pm 1, \pm 2, \ldots,$ and at $t' = (k + 1/2)T$, $k = 0, \pm 1, \pm 2, \ldots,$ respectively. Because of this, the function $\Delta x(t)$ reaches one minimum and one maximum over a period. So the crank rotation period may be determined from the measured dependence $\Delta x(t)$ as the distance along the abscissa axis between two adjacent minima or two adjacent maxima.

It follows from the aforesaid that the initial phase ¨$_{cr0}$ may be determined from the measured dependence $\Delta x(t)$ as follows

$$\varphi_{cr0} = -\frac{2\pi t_1}{T} \tag{5}$$

where t_1 is the time at which the measured dependence $\Delta x(t)$ shows its first maximum (the procedure of finding T and t_1 from the measured dependence $\Delta x(t)$ is illustrated in Fig. 2).

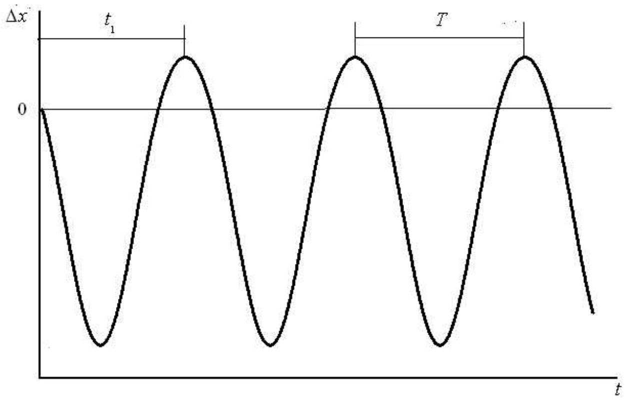

Fig. 2

In view of Eq. (5), the expression of (3) for $\varphi_{cr}(t)$ becomes

$$\varphi_{cr}(t) = \frac{2\pi(t - t_1)}{T}. \tag{6}$$

Given T and t_1, the actual target displacement can be calculated from Eqs. (1), (2), and (6) and compared with the measured one.

However, T and t_1 can be determined from the measured time dependence of the displacement only approximately. Because of this, the displacement measurement error, i. e. the difference of the measured displacement and the actual one may be found by the following algorithm.

1. From the measured time dependence of the target displacement $\Delta x(t)$, estimate the crank rotation period T and the time t_1 at which the measured dependence $\Delta x(t)$ shows its first maximum (in the following, the estimated values of T and the time t_1 will be denoted as T_{ap} and t_{1ap}, respectively).

2. Vary T and t_1 with a specified step on the intervals $0.9T_{ap} \le T \le 1.1T_{ap}$ and $0.9t_{1ap} \le t_1 \le 1.1t_{1ap}$.

3. For each pair (T, t_1), calculate the target displacement at each time point from Eqs. (1), (2), and (6).

4. For each time point, calculate the displacement measurement error Δx_{er} as the difference of the measured displacement $\Delta x(t)$ and the calculated displacement $\Delta x_c(t)$.

5. Find the maximum value $|\Delta x_{er}|_{\max}$ of the displacement error magnitude for the given pair (T, t_1).

6. Find the pair (T, t_1) such that $|\Delta x_{er}|_{\max}$ is a minimum and take these values of T and t_1 as the actual values T_{act} and t_{1act} of the crank rotation period T and the time t_1.

7. For $T = T_{act}$ and $t_1 = t_{1act}$‘, calculate the target displacement at each time point from Eqs. (1), (2), and (6).

8. Run Step 4 to find the actual displacement measurement error Δx_{er}.

To verify the method proposed in [6] by the above algorithm, the displacement of a target (a brass disc or a brass square) put into a reciprocal motion by an electrically driven crank mechanism was measured. The target vibration frequency was controlled by the voltage across the driving motor. The target vibration amplitude was controlled by varying the crank radius.

The measuring setup comprised a microwave oscillator, a circulator with a dummy load, a waveguide section with two probes installed therein and two semiconductor detectors connected to the probes, a horn antenna mounted at the end of the waveguide section, two amplifiers, an analog-to-digital converter, and a personal computer. A schematic of the setup is shown in Fig. 3. The electromagnetic wave generated by the oscillator passes through the circulator, enters the waveguide section, is emitted by the horn antenna, reaches the target, and reflects therefrom. The reflected wave passes through the horn antenna, enters the waveguide section, and is directed by the circulator to the dummy load. The electromagnetic wave generated by the microwave oscillator and the wave reflected from the target interfere in the waveguide section to form a standing wave, whose amplitude is measured with the electrical probes and the semiconductor detectors connected thereto. The amplifiers amplify the detector currents, and the amplified currents arrive at the analog-to-digital convertor, which converts them into digital signals. From the digital signals, the personal computer determinates the relative displacement of the target by the method proposed in [6].

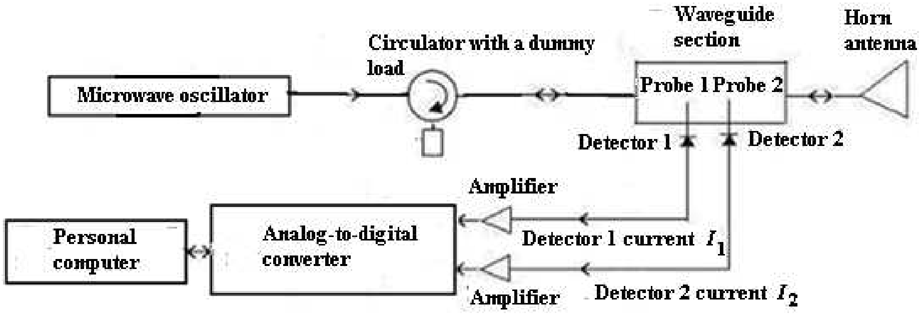

Fig. 3

The experiments were conducted at different values of the target double amplitude equal to twice the crank radius and the minimum distance between the antenna and the target. In all the cases, the free-space operating wavelength was 3 cm, with corresponds to an operating frequency of 10 GHz.

In Experiment 1, the target was a brass disc of diameter 128 mm, the target double amplitude was 15 cm, and the minimum distance between the antenna and the target was 100 cm. In Experiment 2, the target was the same in Experiment 1, the target double amplitude was 10 cm, and the minimum distance between the antenna and the target was 15 cm. In Experiment 3, the target was a 70x70 mm brass square, the target double amplitude was 10 cm, and the minimum distance between the antenna and the target was 5 cm.

Figs. 4 to 6 show the target displacement Δx measured by the method proposed in [6] and the actual target displacement Δx_{act} found by the algorithm described above for Experiments 1, 2, and 3, respectively. As can be seen from the figures, the target vibration period is about 0.5 sec, i.e. the vibration frequency is about 2 Hz. It can also be seen that the curves of the measured and the actual displacement coincide to within the line thickness.

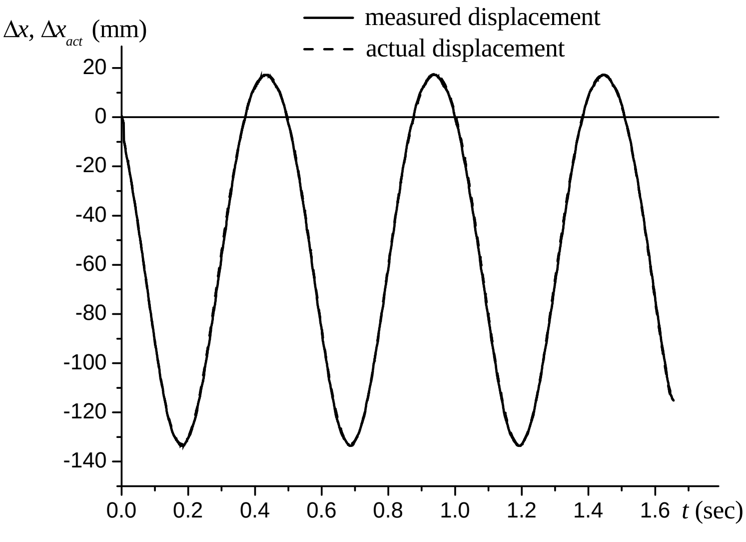

Fig. 4

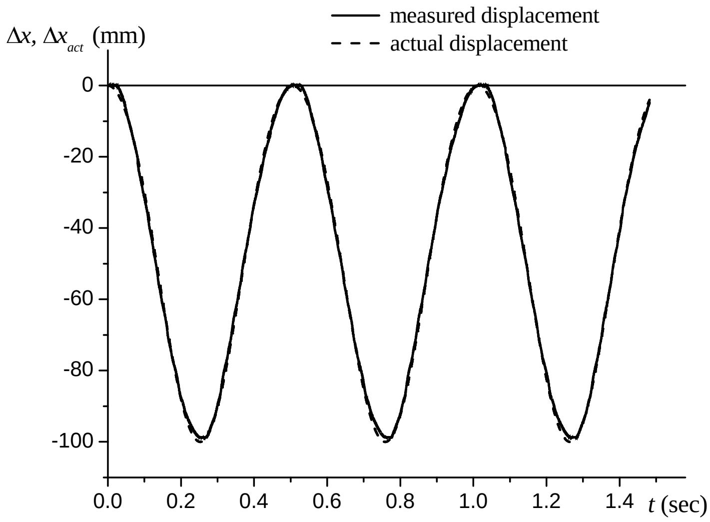

Fig. 5

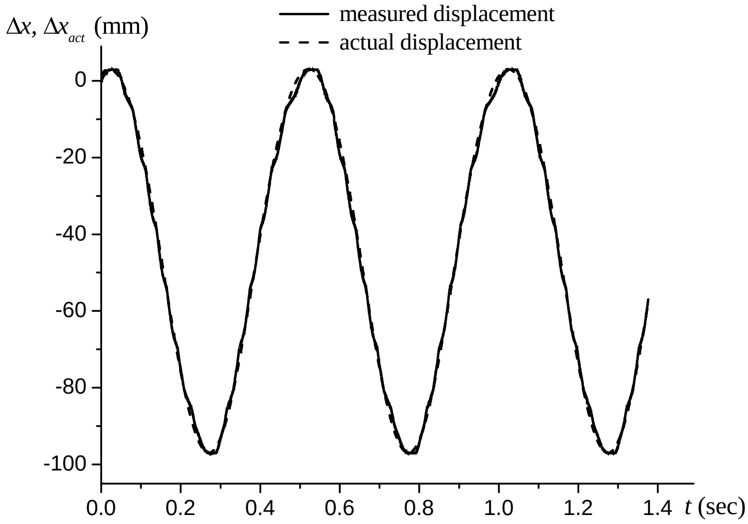

Fig. 6

The peak-to-peak amplitude was determined to an accuracy of 0.7 mm in Experiment 1, 1.1 mm in Experiment 2, and 0.2 mm in Experiment 3.

Figs. 7 to 9 show the displacement measurement error Δx_{er} equal to the difference of the measured displacement Δx and the actual displacement Δx_{act} versus the time and the apparent reflection coefficient r_{ap} versus the target displacement Δx_0 from the position closest to the antenna for Experiments 1, 2, and 3, respectively. The apparent reflection coefficient r_{ap} is defined as the smaller positive root of the biquadratic equation that relates the actual reflection coefficient of the target r_{act} to the currents of the semiconductor detectors [6]. As shown in [6], r_{ap} coincides with r_{act} if the latter is no greater than $1/\sqrt{2} \approx 0{,}707$; otherwise, r_{ap} may not be equal to r_{act}. If $r_{ap} \neq r_{act}$, the displacement is determined with an error, which, however, does not exceed 4.4 % of the free-space operating wavelength.

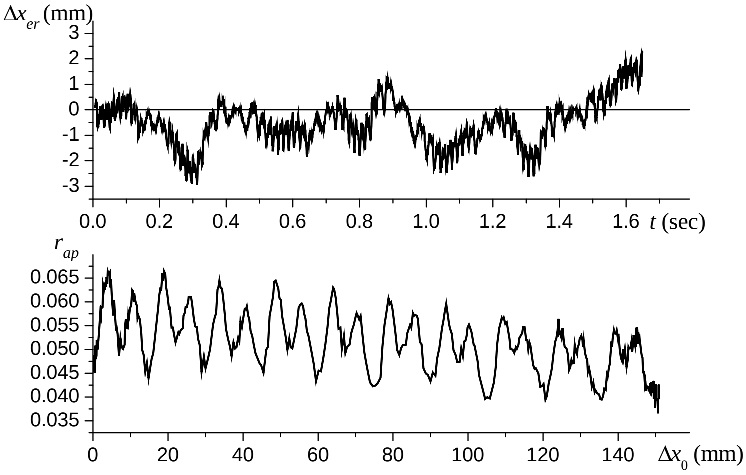

Fig. 7

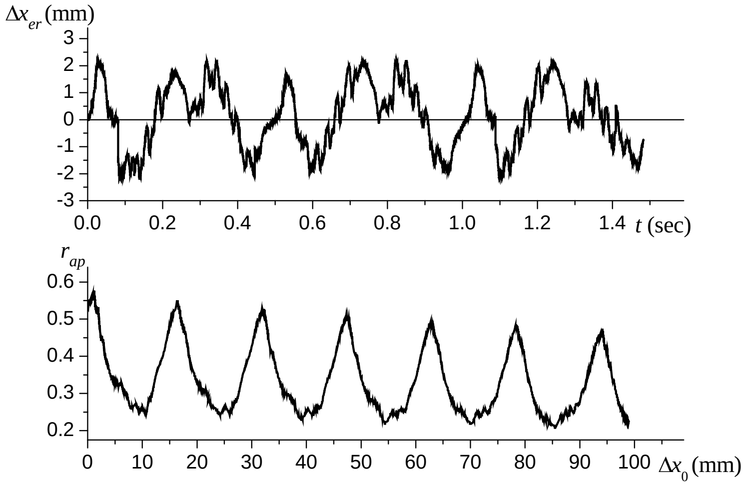

Fig. 8

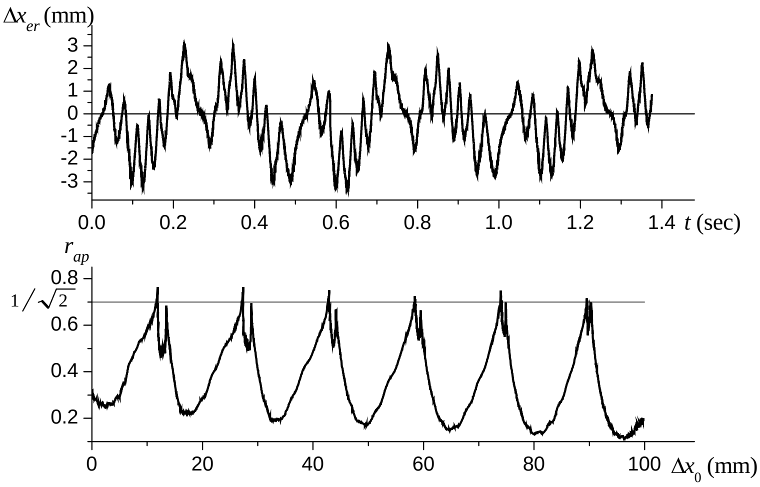

Fig. 9

The maximum and the average error in the determination of the instantaneous relative displacement was 2.9 mm and 0.8 mm in Experiment 1, 2.2 mm and 1.0 mm in Experiment 2, and 3.3 mm and 1.1 mm in Experiment 3. In Experiments 1 and 2, the apparent reflection coefficient varied between 0.04 and 0.066 and between 0.12 and 0.58, respectively, i. e. it was less than $1/\sqrt{2} \approx 0.707$. Because of this, in those experiments the smaller positive root of the biquadratic equation gave the actual reflection coefficient, and thus the error was due to other factors such as deviation of the reflected wave from the plane waveform, reflections from the antenna, noise, etc. In Experiment 3, the apparent reflection coefficient varied between 0.2 and 0.76, i. e. at some of the measurement points the smaller positive root of the biquadratic equation might be extraneous. However, as can be seen from the data given above, this did not contribute much to the error in comparison with Experiments 1 and 2. As can be seen from Figs. 6 and 9 (Experiment 3), the two-probe method proposed in [6] performs well for a minimum antenna–target distance of 5 cm too, while the standing-wave radar proposed in [10] fails to operate at distances less than 14 cm due to positional interference between the target and the antenna.

So the experiments described in this paper have verified the two-probe displacement measurement method proposed in [6], thus confirming that the displacement can be determined from probe measurements at an unknown reflection coefficient using as few as two probes. In comparison with conventional three-probe measurements [11], the reduction in the number of probes simplifies the design and manufacture of the measuring waveguide section and alleviates the problem of interprobe interference. The simple hardware implementation of the above-mentioned displacement measurement method allows one to use it in the development of motion sensors to measure the displacement of space debris objects onboard a dedicated spacecraft for space debris removal [12].

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