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Research and Development of a Multi-Point High-Precision Displacement Measuring System for the Installation Space of Vibration Isolation on Submarine Raft Structures

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Abstract: The well installed status of raft vibration isolation is undoubtedly of great significance in marine engineering, especially for submarines. To achieve this, the accurate measurement of the installation space of the vibration isolation is necessary. The traditional measuring technique has many drawbacks. Therefore, simultaneously measuring the multi-point spacing with high precision between two metal surfaces is the focus of this work. Based on eddy current sensing principle, a multi-point spacing measuring system with a simple structure and good measurement accuracy has been developed and reported. The system includes a sensor array component, an integrated controlling component, and a calibration platform. The measured data from multiple points are obtained at the same time through the sensor array and are uploaded to the host computer and a corresponding LabVIEW program was exploited to display, process, and store the spacing results. Furthermore, the least square algorithm has been employed to calculate the flatness of the measured metal surfaces, and the GUM (guide to the expression of uncertainty in measurement) method has been applied to evaluate the flatness error uncertainty. The experimental tests show that each measuring duration only lasts for seconds to get results and the error uncertainty of the measured surface flatness could reduce to less than 1.0 μm . The developed measuring system has better efficiency and higher precision compared to traditionally manual operations. The measuring and analysis method could also be applied to other related situations.

Keywords: research and development; spacing measuring system; eddy current sensor array; surface flatness; measurement uncertainty analysis



Citation: Yu, Y.; Xu, S.; Wang, M.; Xie, Q. Research and Development of a Multi-Point High-Precision Displacement Measuring System for the Installation Space of Vibration Isolation on Submarine Raft Structures. *Appl. Sci.* **2023**, *13*, 12024. <https://doi.org/10.3390/app132112024>

Academic Editors: Kang Su Kim and Laurent Daudeville

Received: 29 August 2023

Revised: 20 October 2023

Accepted: 2 November 2023

Published: 3 November 2023



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1. Introduction

In marine engineering, floating raft systems are widely used in kinds of ships, warships, submarines and other related structures, equipment, and facilities [1]. Usually, vibration isolators are installed to collect the raft system and base. On the one hand, they could protect the machines and devices installed on the rafts from sudden external shocks under certain circumstances. On the other hand, and more importantly, the floating raft is a key technique for vibration and noise control.

The vibration and noise control are vital for submarines. Normally, a submarine has a circle hull and a relatively long body and the raft system is installed inside compactly. Figure 1 gives a schematic diagram of a floating raft system installed in a submarine [1]. Many vibration isolators are needed between the floating raft structures and supporting base in all directions, along with the hull circle. There are kinds of vibration isolator types, like airbags, also known as gasbags, which are commonly employed due to their large bearing capacity and good vibration isolation performance [2]. As technology advances,

especially at present when anti-submarine technology keeps improving, the underwater quieting performance of submarines has been unprecedentedly challenging [3]. Therefore, any aspects negatively affecting the concealment ability should be considered and avoided.

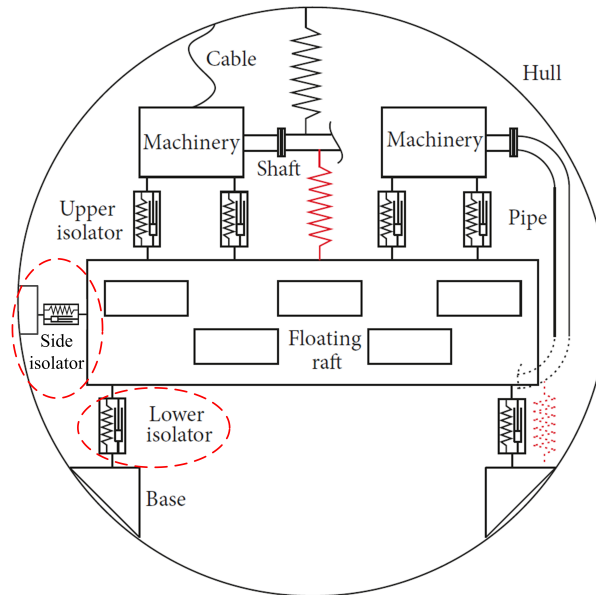


Figure 1. The schematic diagram of vibration isolators for floating rafts in submarines.

Many factors show a great impact on the vibration and noise control performance, such as the isolator type and its installed station. The good installation status of floating raft isolation systems is very important in reducing vibrations and noises which would affect, both directly and prominently, the overall performance. Figure 2 gives an installation schematic diagram of a vibration isolator in the horizontal direction. In the installation area, two metal plates, i.e., the upper backing plate and the lower backing plate in the schematic, are fine machined. This helps get a relatively correct distance between the two plates. For the installing process of big vibration isolators, ideally, it is best to make the vibration isolator height exactly equal to the distance between the base and the surface to be supported. However, the isolators usually could not match the spacing between the base and the distance. When there is a difference between the isolator height and the distance, it is necessary to install adjusting shims [4], which means the sizes of the shims need be obtained. The common way to ascertain the thickness of the shim for the isolator is to manually measure the spacing between the mounting surfaces and then subtract the isolator height. Since the isolator height is usually known, the mounting space needs to be measured.

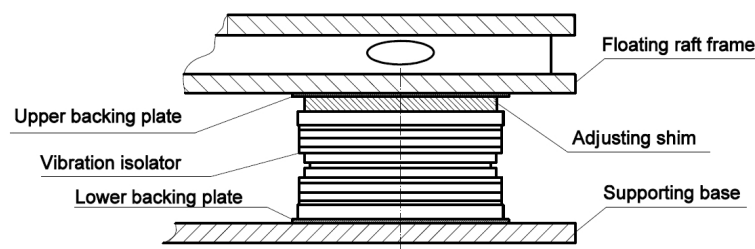


Figure 2. The installation of a vibration isolator between rafts and supporting base.

The traditional technique of measuring the installation space is to use tools like micrometers and vernier calipers, which have many drawbacks. When measuring, operators usually use a vernier caliper, setting it vertical to the mounting plates and ensuring the

two measuring jaws are in contact with the two surfaces. The displacement could then be read and recorded. And the basic dimensions of the shims could be obtained. Afterwards, an initial shim would be manufactured for preinstallation. And the shim will be adjusted several times until a satisfying shim shape is reached. Many problems may show up in the manual measuring processes. Firstly, the measurement accuracy cannot be guaranteed, so that the adjustment shims may be made with large errors, which affects the installation of the rafts and equipment. Secondly, since there are only a few sampling points available during the measurement for adjustment shims, the reconstruction of shim mounting surface is only usually determined by three measured points. In this case, the mounting surfaces of the shims and the rafts may not be in contact effectively. As a result, vibrations and noises could occur and the wear of the shim surfaces may speed up. On the other hand, due to limited operation and installation room, the labor intensity of workers is high and the working efficiency is low. Practice shows it may take minutes for just one single measured point. Furthermore, human mistakes would happen easily. In summary, many problems exist in the present traditional measuring and installing technique. In order to improve the quality and efficiency of vibration isolation installation, the research and development of a fast and accurate measurement system is extremely urgent and of great importance.

As an important indicator for evaluating the planeness quality of the parts [5,6], surface flatness is also significant, in this work, in the vibration isolation performance. In practice, it is necessary to judge whether the manufactured quality of the backing plates is satisfied (see Figure 2). Through multi-point displacement measurements, it is feasible, in some way, to characterize the flatness of a surface. Up until now, the main planeness measuring instruments have included autocollimators [7,8], white light interferometers [9] and the clearance method [10]. CMMs (coordinate measuring machines) are often used to measure large movable planes [11]. Another flatness measuring method is to use a CCD (charge coupled device) camera as a data acquisition instrument and to process the acquired image data to obtain the flatness. The data processing process is relatively complex [12]. Furthermore, an instrument developed based on the laser ranging method [13] is also an option. It generates three-dimensional coordinate information by acquiring a large number of point cloud data [14], and then the error value could be obtained according to a reasonable flatness calculation algorithm [15]. The accuracy of this method is high and the measured data are reliable, whereas the cost is high [16]. These existing measuring instruments and techniques are mainly employed to measure the planeness of a single surface at one time.

Based on the backgrounds mentioned above, in this work, a measuring system was developed for a certain isolator on the basis of high-precision eddy current displacement sensors in order to efficiently obtain the distances at multiple points simultaneously between two metal plates. A matched LABVIEW (Laboratory Virtual Instrumentation Engineering Workbench, National Instruments, NI) program was also exploited for data processing, showing, and analysis. The measured spacing results could be used for calculating the flatness of the metal plates through related data processing. And the system is proven to be valid and it could work efficiently.

The rest of this paper is structured as follows. Section 2 gives the related theories including the measurement principle. Section 3 reports the developed system. The measured results are obtained through experimental tests and discussed in Section 4, followed by the conclusions in Section 5.

2. Theories and Methods

2.1. Sensor Type and Measurement Principle

Displacement measuring methods could be categorized into contact and non-contact types based on whether the measuring probe is in touch with the object to be measured or not. The non-contact type has a wide range of applications due to its many advantages. For example, there is no disturbing or destruction of the object nor the measuring instruments.

There are several types of non-contact displacement sensors and Table 1 lists those that are commonly applied. Each type of sensor has its own advantages and disadvantages. For example, the laser displacement sensor has high measurement accuracy and range, while it demands certain environmental conditions. Through comprehensive comparisons, the eddy current displacement sensor is employed in this work with regard to the actual operation conditions.

Table 1. Commonly used non-contact displacement sensors with ordinary parameters.

No.	Type	Measurement Range	Resolution	Linearity/Error Value	Characteristics
1	Capacitive sensor [17]	0.05–20 mm	0.0007–0.03%	0.2–0.5%FS	Low cost, low power consumption, small positioning space, susceptible to environmental interference [18]
2	Laser displacement sensor [19]	0–18 mm	0.1 μm	0.02%FS	High measurement accuracy, wide range, noise interference can easily lead to data distortion
3	Fiber optic displacement sensor [20]	0–200 mm	0.06 mm	0.16 mm (error)	Wide measuring range, immune to electromagnetic interference
4	Grating displacement sensor [21]	0–90 mm	2.9 μm	-	Rapid response, corrosion resistance, high precision, susceptible to temperature influence
5	Eddy current displacement sensor [22]	2–50 mm	0.3 μm	0.2%FS	Small size, high measurement accuracy [18]

Figure 3 gives a measurement schematic of an eddy current sensor. Based on the electric eddy current effect [23], the sensor could accurately detect the distance between the measured body, namely the target in the schematic, which must be a metallic conductor, and the coil in a probe through the change in electrical signal in the circuits. This method has the advantages of high sensitivity, strong anti-interference ability, non-contact measurement, fast response speed, and being free from oil and water and other factors [18,24,25].

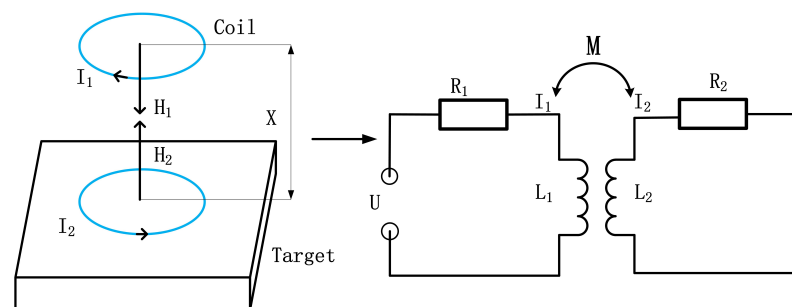


Figure 3. Schematic diagram of an eddy current sensor.

One sensor could measure the displacement to a metal surface on one side. The measuring range is limited. In order to measure the spacing between two surfaces, two opposite sensors could be used. Figure 4 gives the measuring principle for the displacement between two sides, i.e., H . For probe 1, the distance to the surface at side 1, namely h_1 , as shown in the diagram, could be acquired. And, in a similar way, the h_2 could also be measured. As long as the distance between the two oppositely installed probes, i.e., h_3 , is known, the final spacing H could be given by $H = h_1 + h_2 + h_3$.

It is worth noting that, in order to gain the H , a standard platform with a similar structure and known accurate spacing must be prepared. This is the calibration station

that is discussed later. What is more, the measured result is highly relevant to the metal material. A fixed distance to different metals will be measured to vary greatly. Therefore, the eddy current sensor itself must be calibrated. If the metals are different, the calibration process of the corresponding sensors should be based on the specified material.

The measuring range of this method is double the single-side measuring and it is applied in this work due to the range requirements and other considerations.

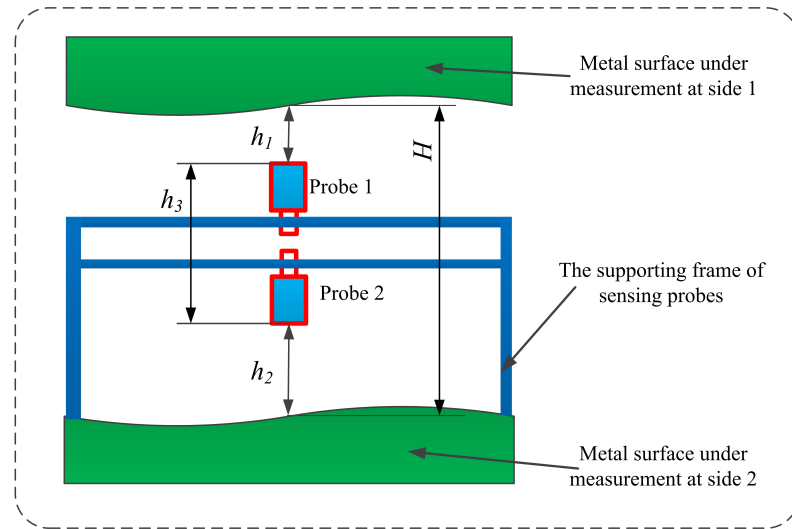


Figure 4. Schematic diagram of clearance measurement.

For measured a big area, several groups of sensors would be arranged. One group refers to two oppositely installed sensors. The distance between every two groups should be paid attention to. It cannot be too small so as to avoid the eddy interactions of two adjacent eddy current sensors.

2.2. Planeness Error Evaluation Model

It is possible to calculate the flatness of a metal surface if the multi-point spacing to a certain ideal plane is obtained. The planeness error refers to the variation of the measured actual surface relative to the ideal plane. The key to error evaluation is to find the ideal plane with the minimum condition [26,27]. Let the ideal plane equation be as follows:

$$z = ax + by + c \quad (1)$$

The least square method is used in this work to evaluate the planeness of the measured surface, and the error function is constructed from the set ideal plane equation:

$$S = \sum (ax_i + by_i + c - z_i)^2 \quad (2)$$

In order to minimize the value of S , which is the distance from each point to the plane, it should be satisfied that $\frac{\partial S}{\partial a}$, $\frac{\partial S}{\partial b}$, and $\frac{\partial S}{\partial c}$ are all 0. Then, we can obtain the following:

$$\begin{cases} \sum 2(ax_i + by_i + c - z_i)x_i = 0 \\ \sum 2(ax_i + by_i + c - z_i)y_i = 0 \\ \sum 2(ax_i + by_i + c - z_i) = 0 \end{cases} \quad (3)$$

In the equations, i means the serial number of the measuring point. Arrange these equations, then obtain the following:

$$\begin{cases} a \sum x_i^2 + b \sum x_i y_i + c \sum x_i = \sum z_i x_i \\ a \sum x_i y_i + b \sum y_i^2 + c \sum y_i = \sum z_i y_i \\ a \sum x_i + b \sum y_i + cn = \sum z_i \end{cases} \quad (4)$$

Change the equation into the matrix form:

$$\begin{vmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i \\ \sum x_i & \sum y_i & n \end{vmatrix} * \begin{vmatrix} a \\ b \\ c \end{vmatrix} = \begin{vmatrix} \sum z_i x_i \\ \sum z_i y_i \\ \sum z_i \end{vmatrix} \quad (5)$$

Bring the x , y , and z values of each measuring point into the matrix equation and then the equation coefficients, a , b , and c , could be obtained as well as the plane equation. The distance from each measuring point to the fitting plane, i.e., d_i , is given by

$$d_i = \frac{z - ax_i - by_i - c}{\sqrt{a^2 + b^2 + 1}} \quad (6)$$

Set the point $P_{max}(x_M, y_M, z_M)$ as the maximum deviation from each measuring point to the least square plane, and the $P_{min}(x_L, y_L, z_L)$ minimum deviation from each measuring point to the least square plane. Then, the planeness could be calculated by

$$f = (d_i)_{max} - (d_i)_{min} = \frac{(z_M - z_L) - a(x_M - x_L) - b(y_M - y_L)}{\sqrt{a^2 + b^2 + 1}} \quad (7)$$

The above equations calculating the surface planeness are commonly used in many previous works, like in reference [27].

2.3. Analysis of Planeness Measurement Uncertainty Based on GUM

For the sake of judging the flatness results objectively and reasonably, the most widely used uncertainty evaluation method at present [28,29], namely the GUM (guide to the expression of uncertainty in measurement) is adopted to analyze the measurement uncertainty. Firstly, the measurement method and measurement device parameters need to be defined. Then, a mathematical model would be established and the uncertainty components will be introduced separately, calculated, and synthesized together. And, finally, the uncertainty results could be acquired [30]. According to the planeness calculated using the equation described above, the transfer coefficients of each parameter are listed as follows:

$$\begin{cases} \frac{\partial f}{\partial x_M} = \frac{-a}{\sqrt{a^2 + b^2 + 1}} \\ \frac{\partial f}{\partial x_L} = \frac{a}{\sqrt{a^2 + b^2 + 1}} \end{cases} \quad (8)$$

$$\begin{cases} \frac{\partial f}{\partial y_M} = \frac{-b}{\sqrt{a^2 + b^2 + 1}} \\ \frac{\partial f}{\partial y_L} = \frac{b}{\sqrt{a^2 + b^2 + 1}} \end{cases} \quad (9)$$

$$\begin{cases} \frac{\partial f}{\partial z_M} = \frac{1}{\sqrt{a^2 + b^2 + 1}} \\ \frac{\partial f}{\partial z_L} = \frac{-1}{\sqrt{a^2 + b^2 + 1}} \end{cases} \quad (10)$$

$$\begin{cases} \frac{\partial f}{\partial a} = \frac{x_L - x_M}{\sqrt{a^2 + b^2 + 1}} - \frac{a[z_M - z_L - a(x_M - x_L) - b(y_M - y_L)]}{(a^2 + b^2 + 1)^{\frac{3}{2}}} \\ \frac{\partial f}{\partial b} = \frac{y_L - y_M}{\sqrt{a^2 + b^2 + 1}} - \frac{b[z_M - z_L - a(x_M - x_L) - b(y_M - y_L)]}{(a^2 + b^2 + 1)^{\frac{3}{2}}} \end{cases} \quad (11)$$

Analyze the uncertainty of each parameter. Assume that the uncertainty of a single measuring point is u_0 , and the measured plane is parallel to the xoy plane. Therefore, the uncertainty of z is the main uncertainty factor of a single measuring point, and the uncertainty is as follows:

$$\mu(Z_M) = \mu(Z_L) = \mu_0 \quad (12)$$

The uncertainty of coefficients a and b are calculated as follows:

$$S = \begin{bmatrix} n & \sum x_i & \sum x_i \\ \sum x_i & \sum x_i^2 & \sum x_i y_i \\ \sum y_i & \sum x_i y_i & \sum y_i^2 \end{bmatrix} \quad (13)$$

To simplify the equation representation, make the setups $p = \sum x_i$, $q = \sum y_i$, $\mu = \sum x_i^2$, $v = \sum y_i^2$, $w = \sum x_i y_i$. Then, S is expressed as follows: $S = n\mu v + 2pqw - q^2\mu - p^2v - nw^2$. The expressions of a and b are given, respectively, by

$$a = \frac{(wq - pv) \sum z_i}{S} + \frac{(nv - q^2) \sum x_i z_i - (pq - nw) \sum y_i z_i}{S} \quad (14)$$

$$b = \frac{(pw - qu) \sum z_i}{S} + \frac{(pq - nw) \sum x_i z_i - (nu - p^2) \sum y_i z_i}{S} \quad (15)$$

Then, the measurement uncertainties of a and b are, respectively, followed by

$$u(a) = \sqrt{u_0 \sum_{i=1}^n \left(\frac{\partial a}{\partial z_i} \right)^2} = \frac{(wq - pv) + (nu - q^2)p + (pq - nw)q}{S} \cdot u_0 \quad (16)$$

$$u(b) = \sqrt{u_0 \sum_{i=1}^n \left(\frac{\partial b}{\partial z_i} \right)^2} = \frac{(pw - qu) + (pq - nw)p + (nu - p^2)q}{S} \cdot u_0 \quad (17)$$

Finally, the synthetic measurement uncertainty of the flatness could be described by

$$u_f = \sqrt{\left[\frac{\partial f}{\partial Z_M} u(Z_M) \right]^2 + \left[\frac{\partial f}{\partial Z_L} u(Z_L) \right]^2 + \left[\frac{\partial f}{\partial a} u(a) \right]^2 + \left[\frac{\partial f}{\partial b} u(b) \right]^2} \quad (18)$$

3. Design and Development of the Measuring System

Measuring the spacing between metal surfaces is the main function of the sensing system introduced in the present work. The system includes hardware and the matched software. The overall framework of the system is shown in Figure 5. The eddy current displacement sensor device transmits the collected displacement data to the upper computer software for processing, showing, and preservation. The software interface would display the distance between the sensors and the metal surface, the spacing between the two metal surfaces at each measuring point, and the flatness of the metal surface to be measured.

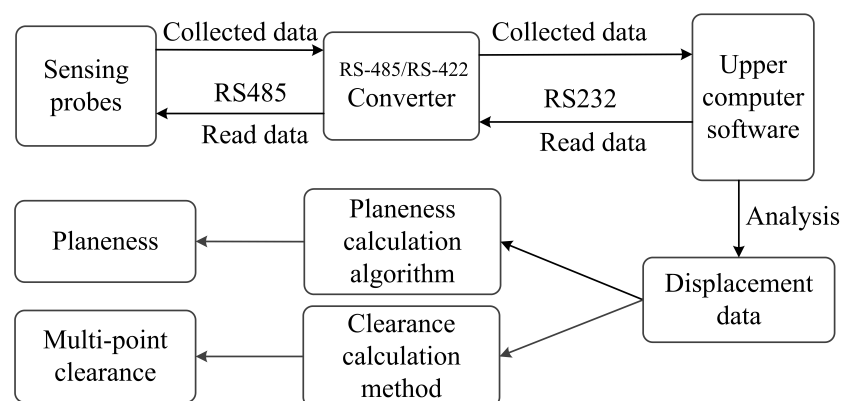


Figure 5. General framework of the system.

3.1. Hardware Design of the System

According to the measuring principle, the size of vibration isolators, and the practical application demand, we designed and developed the measuring system, including a sensor array component and an integrated controlling component. The sensor array component

mainly contains multiple sensors and a mounting frame. And the controlling component is composed of other related parts.

For the sensor array component, the ML33-25-00-02 eddy current displacement sensor, produced by China MIRAN Technology (Shenzhen Miran Technology Co., Ltd., Shenzhen, China), has been chosen. This type has a measurement range of 20 mm, a resolution of 1.0 μm , and a signal output using the RS485 communication mode (see Table 2). Figure 6 gives a photograph of the eddy current sensor. The probe is for detecting displacement. The preprocessor is the signal processing center of the whole sensor system. On the one hand, the preprocessor would provide a high-frequency AC excitation current to the probe coil and make the probe work. On the other hand, through a special circuit, the preprocessor could sense the gap between the probe and the metal conductor to be measured. After processing, the electric output signal will be outputted, which changes linearly with the gap.

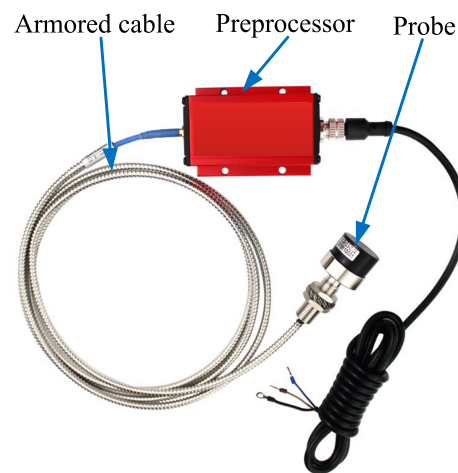


Figure 6. A photograph of an eddy current sensor applied in this work.

Table 2. Related specifications of the sensor used.

No.	Item	Value
1	Sensor range	20 mm
2	Probe diameter	40 mm
3	Liner error	$\leq \pm 1\% \text{FS}$
4	Resolution	1.0 μm
5	Probe weight	0.20 kg
6	Preprocessor weight	0.35 kg

Since the installation size of the vibration isolators is about $600 \times 600 \times 300 \text{ mm}$, 11 groups of sensors in total are set with a staggered layout, and the distance between each of them is at least 100 mm, which could avoid the cross interference on electromagnetism from the adjacent probe. Furthermore, based on the considerations of installation space and the probe size, the main dimensions of the frame are designed as $550 \times 450 \times 215 \text{ mm}$. The supporting frame for the sensors should have reliable stiffness and stability to guarantee the measured results. Moreover, it should be lightweight; only in this way can it be handled easily and conveniently. Consequently, unlike a traditional assembly, one-piece 3D printing technology was employed to make the mounting bracket by using non-metallic polymeric materials. To be specific, nylon plastic is applied. Figure 7a gives the structure model of the component in which a mounting frame accounts for the main part.

Advanced computer aided technology has been applied in developing the mounting frame. In order to make sure the light-weighted frame structure has good rigidity and little deformation, finite element analysis has been employed to explore the deformation situation under different loaded conditions. The simulations have been carried out using

commercial software package ANSYS 2022 Release 1.0. Following the normal analysis work flow, the geometry model is designed first and then imported into the computing platform. Since the frame is small and the structure is not complex, there is no need for great computing power and the free meshing method is employed. Control the maximum element size, then the model is meshed, as shown in Figure 7b, which was experienced through a grid independence check. The boundary conditions are loaded including all the probe weights and the frame gravity for simplification. The four corners near the bolt holes are set with fixed condition, since they would be locked by bolts in the real installed status. Figure 7c,d display the frame at horizontal and vertical positions, respectively. It could be found that the deformations are as expected. The maximum is acceptable (less than 0.01 mm), indicating that the designed frame, which is lower than 5 kg, could be used. Furthermore, in the latter formal measuring process, with the help of a standard calibration platform, the error resulting from the deformation could be rectified.

As a consequence, the frame has advantages in mechanical performance, like a good rigidity and light weight, fulfilling the demands for application.

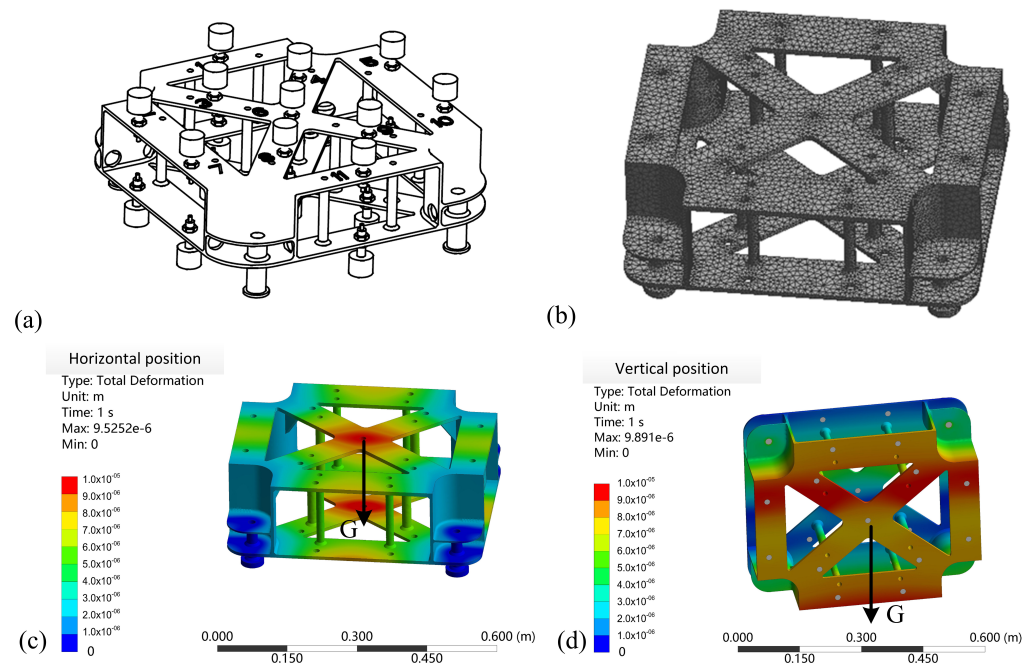


Figure 7. The designed supporting frame. (a) Model of the sensor array component; (b) The meshed geometry being analyzed; (c) The deformation status under horizontal and vertical positions (d).

The integrated controlling component stays in protective housing and is composed of the upper computer, the RS485/RS232 converter, the proximity sensors for each eddy current probe, and the power supply and display module. The upper computer adopts the RS232 communication mode. Through the RS232 to 485/422 passive bidirectional converter UTEK UT-217E (China UTEK technology, UOTEK), data transmission is realized between the sensor and the upper computer. The sensing and controlling components, which are shown, respectively, in Figure 8a,b, are collected and communicated with armoring wires.

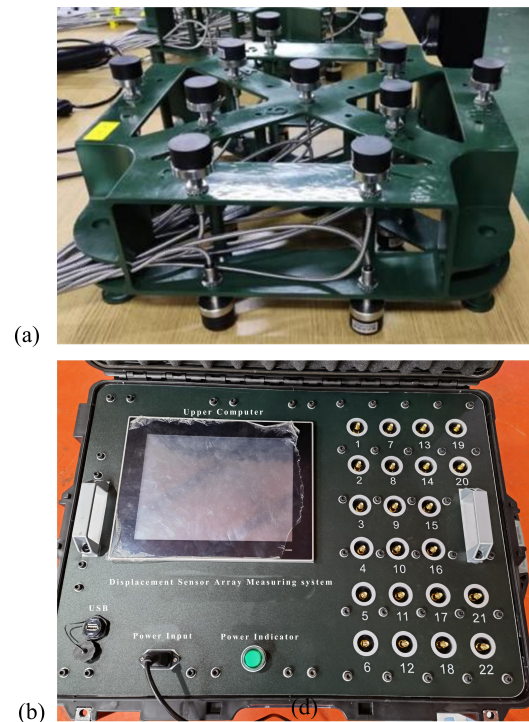


Figure 8. Photographs of the sensor array component (a) and the integrated controlling component (b).

3.2. System Calibration Platform

A calibration platform has been designed and manufactured to obtain the distance between the two sensors of each group. The platform shown in Figure 9 is made up of two standard metal plates. They are connected by long bolts. The spacing and parallelism between the fixed panels could be adjusted by the nuts and finally fixed. The plates are thick enough and have high structural stiffness. Accurate abrasive machining has been used to grind the working surfaces of the plates, resulting in a flatness of no more than $5\ \mu\text{m}$. As with the measuring principle, for each group, the distance between two sensors is the difference value between the spacing of two plates and the measured displacements of the two sensors.

It should be noted that the probe itself must have been calibrated on the same material of the measured surface.

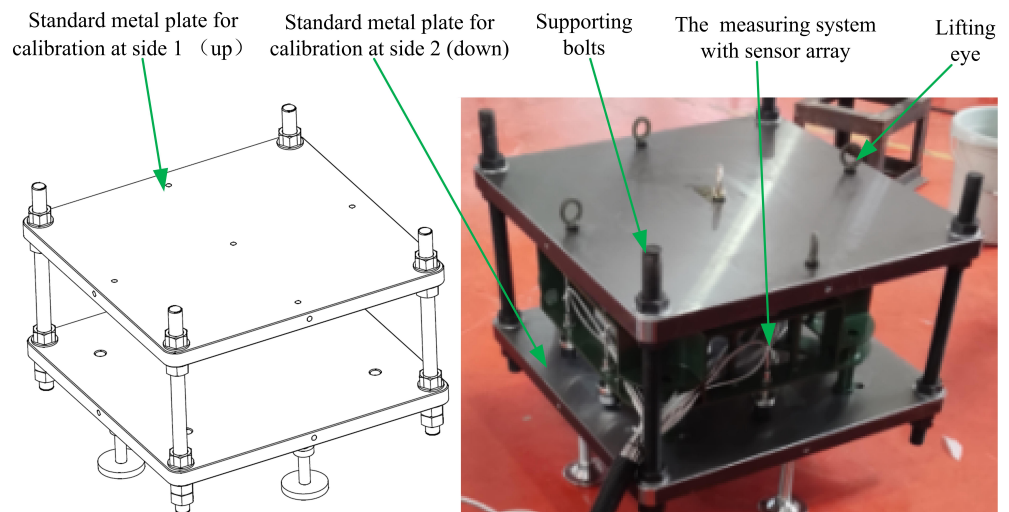


Figure 9. The calibration platform of the measuring system.

3.3. Software Design and Data Algorithm

3.3.1. Measuring System Software

The upper computer software is programmed using LabVIEW R2015. The program has the functions of data acquisition, data processing, visual display, and storage. It includes four modules, i.e., self-check, calibration, measurement, and data analysis. Their main functions are briefly introduced as follows:

(1) Self-inspection module: to check whether the connection between each sensor and the upper computer is successfully established.

(2) Calibration module: to obtain the distance between each group of sensor probes.

(3) Measurement module: to get the distance from each sensor probe to the measured surfaces, and calculate the distance between the two surfaces at each measuring point.

(4) Data analysis module: to display the distribution coordinates of each measuring point, process the obtained data, and calculate the flatness of the tested surface.

The measurement processing workflow diagram is shown in Figure 10.

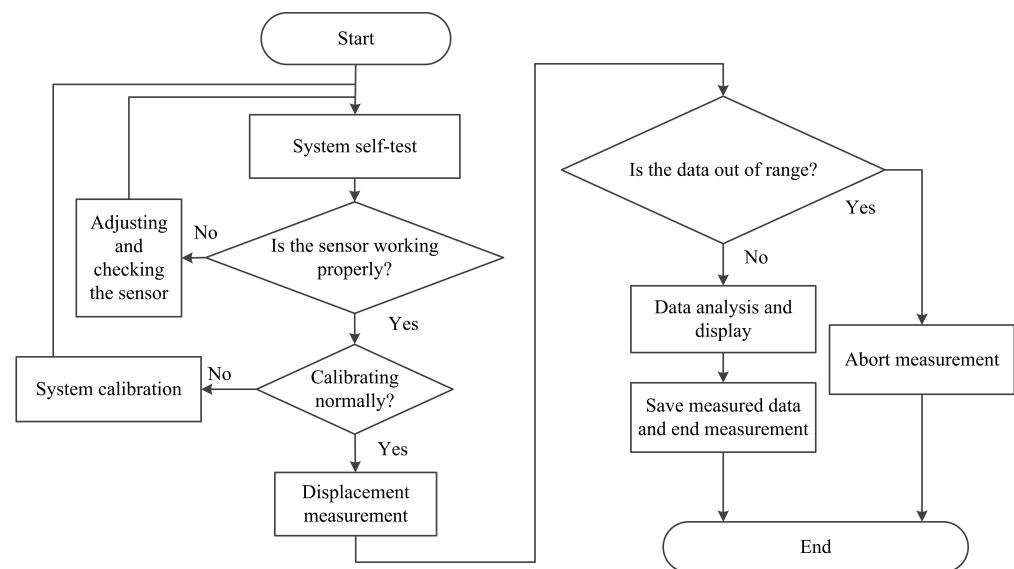


Figure 10. The measurement processing workflow.

3.3.2. Self-Inspection and Calibration Module

The serial port control is configured using VISA (Virtual Instrument Software Architecture) in LabVIEW to read the address information of each sensor, so that its proximator can successfully establish a connection with the computer, and the upper computer can read and analyze the measured data. After beginning, display the self-inspection progress bar via a control. If there is a sensor connection failure, display its number and report. Then, fix it until the self-inspection can complete normally and successfully. The purpose of the calibration module is to obtain the distance between each group of sensor probes. When the sensor array device is placed in the calibration platform, the measured displacement from the sensor probe to the calibrating metal plate will be transmitted to the program for analysis. Following the measuring principle, the known distance H' between the calibration plates is read, and the measured values of each sensor could be gained. Set the distance from the sensor probe 1 to the calibration metal panel 1 as h_1' , and the distance from the other sensor probe to the metal panel 2 as h_2' . Then, the displacement h for a group of probes would be obtained, namely $h = H' - h_1' - h_2'$. After calibration, all the displacements at each group will be stored and saved.

3.3.3. Data Collection and Storage Module

The calibrated system could be used to measure the spacing between two parallel metal surfaces at multi-points. The metal surface must have the same material as the calibration platform and must also meet other requirements like surface roughness, area, and measuring range. A similar platform has been manufactured for experimental tests, which is shown in Figure 11. In the measuring process, the eddy current sensor array gets the displacements, and RS485 communication is employed. The upper computer analyzes the collected data according to the standard Modbus protocol. The distance h between each group of sensor probes is known based on the calibration process. Measure the distance from the sensor probe to the metal plate on one side as h_1 , and the distance from the other sensor probe to the surface on the other side as h_2 . Finally, the distance between the plates at the measured point can be obtained as $H = h + h_1 + h_2$.

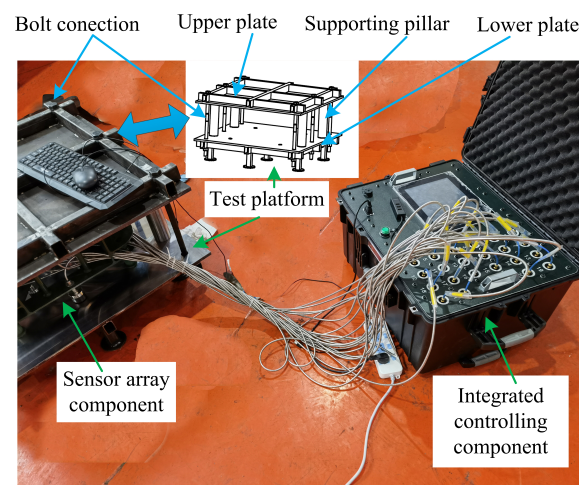


Figure 11. The formal measurement in the test platform.

3.3.4. Data Analysis Module

With respect to the foregoing introduction of the well-manufactured calibration platform with high precision, it is assumed that the platform is standard and has two parallel and base planes in this work. As a consequence, data analysis could be carried out. Firstly, the displacement data obtained using the sensors are from multiple points, therefore these data need to be unified into a coordinate system during processing. After measurement, the distances between the sensors and the measured metal surfaces could be acquired. And the distance between the sensors and the standard plates of the platform have been obtained during the calibration process.

Set a coordinate system to obtain the three-dimensional coordinates of the measuring points of each sensor group. For example, set the lower surface of the calibration platform as the z-axis origin, and the no. 6 sensor group (at the center of the plate) as the x-axis and y-axis origin. Then, calculate the flatness of the measured surfaces. Quite a few theories are suitable, in which the least square method [31,32] is commonly used. Based on the three-dimensional coordinates of each measuring point, firstly solve the linear equation using the matrix method and get an ideal plane equation; and, finally, calculate the distance between each measuring point and the ideal plane. The maximum distance would be defined as the flatness of the measured surface.

4. Results and Discussions

4.1. Data Acquisition

Before starting the measurement, checking the sensor array is strongly recommended, which usually includes the connection between the probes and the mounting frame, the measuring range, and the installed attitude of the sensors. Following the flow diagram of the measuring process (see Figure 10), put the sensor array at the calibration platform

to obtain the distances between sensors at each group. All data would then be stored. Secondly, move the measuring device to the test platform carefully, avoiding bumps, because any change, especially on the sensors, will possibly alter the measurement results during calibration. Finally, start the formal measuring until all the results are acquired and saved. Several tests are carried out and the data are averaged, which helps in reducing unnecessary errors.

The platform, which can be seen in Figure 11, is also designed and assembled with a gap of 260 mm. The calibration and measuring results of the sensor groups are settled and given in Table 3. It took about 5 s to get each measured result during the measuring process, showing increased speed compared to the traditional manual measuring technique.

Table 3. Statistics of the experimental test data.

Sensor Group No.	Distance to Calibration Standard Surface (Top) /mm	Distance to Calibration Standard Surface (Down) /mm	Distance to Test Platform Upper Plate /mm	Distance to Test Platform Upper Plate (Down) /mm	Calibrated Result between Two Sensors /mm	Spacing in Test Platform /mm
1	9.533	6.189	9.527	6.186	244.278	259.991
2	10.896	6.249	10.992	6.158	242.855	260.005
3	10.328	6.171	10.331	6.181	243.500	260.012
4	9.633	7.244	9.529	7.351	243.123	260.003
5	10.200	7.173	10.204	7.181	242.627	260.012
6	11.018	6.396	11.006	6.429	242.586	260.021
7	10.969	6.786	10.961	6.789	242.245	259.995
8	10.892	5.103	10.899	5.104	244.004	260.007
9	9.990	4.976	9.982	4.997	245.034	260.013
10	10.668	5.478	10.671	5.48	243.854	260.005
11	10.599	5.388	10.623	5.357	244.013	259.993

Since the two opposite sensors are set as a group, take the z-axis as the vertical direction for both the upper and lower surfaces, then the direction of the x-axis and y-axis coordinates of the measuring points are the same. The z-axis coordinate values of each measuring point are calculated. The three-dimensional coordinate values are shown in Table 4. Substitute the data into the equations introduced before, and the flatness of the upper and lower metal surfaces could be calculated as 0.1621 mm and 0.155 mm, respectively, in which the process has been omitted since it was just calculated.

Table 4. The coordinates for measuring points.

No.	x Coordinate/mm	y Coordinate/mm	z Coordinate (Top)/mm	z Coordinate (Down)/mm
1	0	245	259.994	0.003
2	−240	90	260.096	0.091
3	−80	120	260.003	−0.01
4	80	120	259.896	−0.107
5	240	90	260.004	−0.008
6	0	0	259.988	−0.033
7	−240	−90	259.992	−0.003
8	−80	−120	260.007	−0.001
9	80	−120	259.992	−0.021
10	240	−90	260.003	−0.002
11	0	−245	260.024	0.031

4.2. Measurement Error Analysis

Any measuring system will have its own error. In a measuring process, some measurement errors come from multiple aspects, including operations, external environment, the measuring device itself, and other factors [33,34], thus finally affecting the measurement accuracy. Therefore, it is significant to examine the measurement error helping in determining the confidence level. In this work, the designed surface spacing and flatness measurement scheme would have certain errors from the data acquisition device, mechanical processing and assembly, data processing scheme, and error evaluation algorithm.

The main errors are listed in Table 5. The eddy current displacement sensor used has a range of 20 mm, a resolution of 1.0 μm , and a linear error of $\pm 1\%$ FS (see Table 2). The standard metal plates of the calibration platform are finely manufactured using abrasive machining with a flatness of ± 0.005 mm. During installation, the two plates of the calibration platform are connected by long bolts, fixed by gaskets and nuts, and the spacing can be manually adjusted. The assembly error is also evaluated.

Table 5. Statistical table of error sources.

No.	Error Source	Error Value
1	Eddy current displacement sensor	$\pm 1\%$ FS
2	Calibration board	± 0.005 mm
3	Parts processing and assembly error	± 0.02 mm

Based on the GUM method for flatness uncertainty analysis, the uncertainty of a single point measurement is u_0 , and its uncertainty is mainly composed of the following aspects:

(1) u_{ev} from the environment.

During the experiment, the laboratory is kept dry and at a constant temperature, so the uncertainty caused by the humidity and temperature of the environment is negligible. The value $u_{ev} = 0$ is considered in further calculations.

(2) u_{res} due to the sensor resolution.

Based on the performance of the eddy current displacement sensors employed in this work, a resolution of 1.0 μm could be obtained, resulting in an uncertainty of $u_{res} = 0.29$ μm through the calculation.

(3) u_{rep} resulted from the repeatability measurement.

Under the same conditions, the Class A uncertainty evaluation method [35] could be adopted for the uncertainty of repeated measurements at the same measuring point. The uncertainty caused by repetitive measurement is prominently caused by the data in the z-axis. We could randomly choose several measuring points for repeated measurement, and then the repeatability error could be calculated according to the Bessel formula [36]. For the sake of conservation, the maximum error value is selected as the uncertainty caused by repetitive measurement and set to u_0 . The uncertainty derived from the Bessel formula is given by

$$u_i = \sqrt{\frac{\sum_{j=1}^n (Z_j - \bar{Z})^2}{n(n-1)}} \quad (19)$$

where u_i is the uncertainty of the five repeated measurements at the point i , n is the number of repeated measurements, and z is the averaged value of the five measurement results.

In this work, measuring points 3, 5, and 9 are selected for five repeated measurements. The measured data are shown in Table 6.

Table 6. Repeated measurement results at the measuring point.

No.	No.3 Point/mm	No.5 Point/mm	No.9 Point/mm
1	10.329	10.201	9.990
2	10.331	10.202	9.991
3	10.330	10.202	9.992
4	10.328	10.200	9.990
5	10.330	10.199	9.991
Averaged value	10.330	10.201	9.991

Taking the data in the table into Equation (19), we can obtain $u_3 = 0.5099 \mu\text{m}$, $u_5 = 0.5831 \mu\text{m}$, and $u_9 = 0.3742 \mu\text{m}$. Then, summing up, the $u_{rep} = 0.5831 \mu\text{m}$ is obtained. As a consequence, the uncertainty of a single point measurement could be received as

$$u_0 = \sqrt{(u_{ev}^2 + u_{res}^2 + u_{rep}^2)} = 0.6512 \mu\text{m}.$$

Finally, bring the coordinate values of the measuring points in Table 4 into the equations from Equations (8)–(18), and the measured data can be obtained from the planeness measuring device. The planeness can be calculated using the least square method, and the uncertainty evaluated using GUM could be obtained as $u_f = 0.9209 \mu\text{m}$, which could meet the expected requirements.

5. Conclusions

The traditional way of measuring the installation space of the vibration isolation for raft structures has many problems, like low accuracy, large measurement error, and tedious multi-point measurement steps. This work tries to achieve the fast and accurate measurement of the installation space. The spacing measurement between two parallel metal surfaces was concentrated. A measuring system composed of multi eddy current sensors, a controlling component, as well as a calibration platform has been designed and developed. The experimental tests show the developed system works well and can obtain the digital spacing results once in several seconds and with relatively high precision, which has many more advantages than the traditional ways. The surface flatness of the measured metal plates could also be evaluated. The measuring system could be employed in other related applications. And the corresponding scheme and method could be employed as a guide or inspiration under other probable circumstances. Specifically, several conclusions can be drawn as follows.

(1) A scheme that can simultaneously measure the multi-point distance between two metal surfaces has been developed, in which the surface flatness could also be analyzed through modeling.

(2) The hardware designs, based on an eddy current displacement sensor, were introduced as well as the software program based on LabVIEW. The purpose of the measurement scheme, mechanical design, software development, algorithm implementation, and test measurement results and analysis were detailed and elaborated.

(3) The experimental tests demonstrated that the proposed scheme can realize fast displacement measurement and flatness analysis. The tests show that each measurement only takes several seconds to obtain results. And the uncertainty of the measurement error could reach less than $1.0 \mu\text{m}$, which meets the requirements of automatic high-precision measurement.

Author Contributions: Conceptualization, Q.X. and S.X.; methodology, Y.Y., S.X. and M. W.; software, M.W. and Q.X.; formal analysis, S.X., M.W. and Y.Y.; investigation, Y.Y., S.X., M.W. and Q.X.; data curation, M.W.; writing—original draft preparation, Q.X., M.W. and Y.Y.; writing—review and editing, S.X. and Q.X.; supervision, Q.X. and S.X.; project administration, Q.X.; funding acquisition, Q.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: Author Shuisheng Xu was employed by the company Tonking New Energy Technology (Jiangshan) Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Ren, L.; Li, Y.; Huang, X.; Hua, H. Dynamic Modeling and Characteristic Analysis of Floating Raft System with Attached Pipes. *Shock Vib.* **2017**, *2017*, 9135715. [\[CrossRef\]](#)
- Niu, J.; Song, K.; Lim, C. On active vibration isolation of floating raft system. *J. Sound Vib.* **2005**, *285*, 391–406. [\[CrossRef\]](#)
- Li, X.; Cai, W.; Ren, N.; Sun, S. The Effect of the Fillets on Submarine Wake Field and Propeller Unsteady Bearing Force. *J. Mar. Sci. Eng.* **2023**, *11*, 727. [\[CrossRef\]](#)
- Lv, X. Small mechanical vibration reduction system based on adaptive hydraulic gasket. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *634*, 12045. [\[CrossRef\]](#)
- Miko, B. Assessment of flatness error by regression analysis. *Measurement* **2021**, *171*, 108720. [\[CrossRef\]](#)
- Shu, H.; Zou, C.L.; Chen, J.Y.; Wang, S.H. Research on Micro/Nano Surface Flatness Evaluation Method Based on Improved Particle Swarm Optimization Algorithm. *Front. Bioeng. Biotechnol.* **2021**, *9*, 775455. [\[CrossRef\]](#)
- Bitou, Y.; Kondo, Y. High-lateral-resolution scanning deflectometric profiler using a commercially available autocollimator. *Meas. Sci. Technol.* **2014**, *25*, 95202. [\[CrossRef\]](#)
- Chen, M.Y.; Takahashi, S.; Takamasu, K. Multi-beam angle sensor for flatness measurement of mirror using circumferential scan technology. *Int. J. Precis. Eng. Manuf.* **2016**, *17*, 1093–1099. [\[CrossRef\]](#)
- Montonen, R.; Kassamakov, I.; Haeggstrom, E.; Osterberg, K. Quantifying height of ultraprecisely machined steps on oxygen-free electronic copper disc using Fourier-domain short coherence interferometry. *Opt. Eng.* **2016**, *55*, 14103. [\[CrossRef\]](#)
- Ameta, G.; Davidson, J.K.; Shah, J. Influence of form on Tolerance-Map-generated frequency distributions for 1D clearance in design. *Precis. Eng.* **2010**, *34*, 22–27. [\[CrossRef\]](#)
- Wang, J.; Sun, Q.C.; Yuan, B. Novel on-machine measurement system and method for flatness of large annular plane. *Meas. Sci. Technol.* **2020**, *31*, 15004. [\[CrossRef\]](#)
- Zhao, L.; Ouyang, Q.; Chen, D.; Zhang, X.; Zhang, Y. Study on CCD laser scanning flatness measurement method for hot rolled strip. *Ironmak. Steelmak.* **2015**, *42*, 600–607. [\[CrossRef\]](#)
- Tan, V.J.; He, S.Y. Oscillation FPCB micromirror based triangulation laser rangefinder. *J. Micromech. Microeng.* **2020**, *30*, 95008. [\[CrossRef\]](#)
- Park, H.S.; Tuladhar, U.M. Robust Inspection Technique for Detection of Flatness Defects of Oil Pans. *Int. J. Automot. Technol.* **2016**, *17*, 119–126. [\[CrossRef\]](#)
- Li, F.X.; Li, H.; Kim, M.K.; Lo, K.C. Laser Scanning Based Surface Flatness Measurement Using Flat Mirrors for Enhancing Scan Coverage Range. *Remote Sens.* **2021**, *13*, 714. [\[CrossRef\]](#)
- Yan, S.Y.; Yang, G.H.; Li, Q.Y.; Wang, Y.; Wang, C.H. Research of Distance-Intensity Imaging Algorithm for Pulsed LiDAR Based on Pulse Width Correction. *Remote Sens.* **2022**, *14*, 507. [\[CrossRef\]](#)
- Ye, Y.; Zhang, C.; He, C.; Wang, X.; Huang, J.; Deng, J. A Review on Applications of Capacitive Displacement Sensing for Capacitive Proximity Sensor. *IEEE Access* **2020**, *8*, 45325–45342. [\[CrossRef\]](#)
- George, B.; Tan, Z.; Nihtianov, S. Advances in Capacitive, Eddy Current, and Magnetic Displacement Sensors and Corresponding Interfaces. *IEEE Trans. Ind. Electron.* **2017**, *64*, 9595–9607. [\[CrossRef\]](#)
- Dong, Z.; Sun, X.; Chen, C.; Sun, M. A Fast and On-Machine Measuring System Using the Laser Displacement Sensor for the Contour Parameters of the Drill Pipe Thread. *Sensors* **2018**, *18*, 1192. [\[CrossRef\]](#)
- Zheng, Y.; Yu, J.; Zhu, Z.W.; Zeng, B.; Yang, C. Design, sensing principle and testing of a novel fiber optic displacement sensor based on linear macro-bending loss. *Optik* **2021**, *242*, 167194. [\[CrossRef\]](#)
- Guo, Y.; Liu, W.; Xiong, L.; Kuang, Y.; Wu, H.; Liu, H. Fiber Bragg Grating Displacement Sensor with High Abrasion Resistance for a Steel Spring Floating Slab Damping Track. *Sensors* **2018**, *18*, 1899. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ripka, P.; Blažek, J.; Mirzaei, M.; Lipovský, P.; Šmelko, M.; Draganová, K. Inductive Position and Speed Sensors. *Sensors* **2020**, *20*, 65. [\[CrossRef\]](#) [\[PubMed\]](#)
- Nabavi, M.R.; Nihtianov, S.N. Design Strategies for Eddy-Current Displacement Sensor Systems: Review and Recommendations. *IEEE Sens. J.* **2012**, *12*, 3346–3355. [\[CrossRef\]](#)
- Li, W.; Wang, H.B.; Feng, Z.H. Non-contact online thickness measurement system for metal films based on eddy current sensing with distance tracking technique. *Rev. Sci. Instrum.* **2016**, *87*, 45005. [\[CrossRef\]](#) [\[PubMed\]](#)

25. Zhao, G.F.; Ying, J.; Wu, L.; Feng, Z.H. Eddy current displacement sensor with ultrahigh resolution obtained through the noise suppression of excitation voltage. *Sens. Actuators A-Phys.* **2019**, *299*, 111622. [[CrossRef](#)]
26. Maculotti, G.; Feng, X.B.; Su, R.; Galetto, M.; Leach, R. Residual flatness and scale calibration for a point autofocus surface topography measuring instrument. *Meas. Sci. Technol.* **2019**, *30*, 75005. [[CrossRef](#)]
27. Zhang, M.W.; Liu, Y.M.; Sun, C.Z.; Wang, X.M.; Tan, J.B. Precision measurement and evaluation of flatness error for the aero-engine rotor connection surface based on convex hull theory and an improved PSO algorithm. *Meas. Sci. Technol.* **2020**, *31*, 85006. [[CrossRef](#)]
28. Strbac, B.; Radlovacki, V.; Spasic-Jokic, V.; Delic, M.; Hadzistevic, M. The Difference Between GUM and ISO/TC 15530–15533 Method to Evaluate the Measurement Uncertainty of Flatness by a CMM. *Mapan-J. Metrol. Soc. India* **2017**, *32*, 251–257.
29. Leal, J.E.S.; da Silva, J.A.; Arencibia, R.V. Contributions to the adaptive Monte Carlo method. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 462. [[CrossRef](#)]
30. Jalid, A.; Hariri, S.; Gharad, A.E.; Senelaer, J.P. Comparison of the GUM and Monte Carlo methods on the flatness uncertainty estimation in coordinate measuring machine. *Int. J. Metrol. Qual. Eng.* **2016**, *7*, 302. [[CrossRef](#)]
31. Lin, S.; Jusko, O.; Hartig, F.; Seewig, J. A least squares algorithm for fitting data points to a circular arc cam. *Measurement* **2017**, *102*, 170–178. [[CrossRef](#)]
32. Sun, J.; Shan, P.F.; Wei, Z.; Hu, Y.H.; Wang, Q.L.; Peng, W.; Zhang, D.H. Data-based flatness prediction and optimization in tandem cold rolling. *J. Iron Steel Res. Int.* **2021**, *28*, 563–573. [[CrossRef](#)]
33. Jywe, W.Y.; Hsieh, T.H.; Chen, P.Y.; Wang, M.S. An Online Simultaneous Measurement of the Dual-Axis Straightness Error for Machine Tools. *Appl. Sci.* **2018**, *8*, 2130. [[CrossRef](#)]
34. Yang, D.L.; Zou, J.G. Precision Analysis of Flatness Measurement Using Laser Tracker. *Int. J. Precis. Eng. Manuf.* **2022**, *23*, 721–732. [[CrossRef](#)]
35. Underwood, J.M. Uncertainty analysis for ac-dc difference measurements with the AC Josephson Voltage Standard. *Metrologia* **2018**, *56*, 15012. [[CrossRef](#)]
36. Gebhardt, H.S.G.; Jeong, D. Fast and accurate computation of projected two-point functions. *Phys. Rev. D* **2018**, *97*, 23504. [[CrossRef](#)]

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