

MEASUREMENT OF NUCLEAR FUEL ROD DEFORMATION USING AN IMAGE PROCESSING TECHNIQUE

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In this paper, a deformation measurement technology for nuclear fuel rods is proposed. The deformation measurement system includes a high-definition CMOS image sensor, a lens, a semiconductor laser line beam marker, and optical and mechanical accessories. The basic idea of the proposed deformation measurement system is to illuminate the outer surface of a fuel rod with a collimated laser line beam at an angle of 45 degrees or higher. For this method, it is assumed that a nuclear fuel rod and the optical axis of the image sensor for observing the rod are vertically composed. The relative motion of the fuel rod in the horizontal direction causes the illuminated laser line beam to move vertically along the surface of the fuel rod. The resulting change of the laser line beam position on the surface of the fuel rod is imaged as a parabolic beam in the high-definition CMOS image sensor. An ellipse model is then extracted from the parabolic beam pattern. The center coordinates of the ellipse model are taken as the feature of the deformed fuel rod. The vertical offset of the feature point of the nuclear fuel rod is derived based on the displacement of the offset in the horizontal direction. Based on the experimental results for a nuclear fuel rod sample with a formation of surface crud, an inspection resolution of 50 μm is achieved using the proposed method. In terms of the degree of precision, this inspection resolution is an improvement of more than 300% from a 150 μm resolution, which is the conventional measurement criteria required for the deformation of neutron irradiated fuel rods.

KEYWORDS : Nuclear Fuel Rod, Deformation, Laser, Line, Inspection, High Definition Image Sensor, Image Processing

1. INTRODUCTION

During the normal operation of a nuclear reactor, a nuclear fuel rod undergoes neutron-irradiation growth, that is, the fuel rod grows in length, due to the neutron creep phenomena. In order to evaluate the integrity of a neutron-irradiated fuel rod assembly after the normal operating cycle of a nuclear power plant, the overall deformation of the nuclear fuel rod is first inspected through a visual test (VT). During the VT, such elements as the crud formed on the surface of the nuclear fuel rod, oxidation film formation, deformation of the fuel rod by bending and bowing, and particularly the degree of fretting wear due to the friction between the fuel rod and spacer grid are carefully observed [1]. The diameter and length of the fuel rod for a pressurized water reactor (PWR) plant, are 9.53/9.66 mm and 4 m [2]. An evaluation of the fuel rod integrity is executed for reactor safety during the next operating cycle of the nuclear power plant. If the deformation of the neutron-irradiated fuel rod exceeds the allowable limit prescribed in the nuclear regulation

guide, the deformed rod is not reloaded into the reactor during the next operating cycle of the plant. For this reason, a high-precision VT that can measure the deformation of the fuel rod at as high a resolution as possible is required. In this paper, a high-precision inspection system for nuclear fuel rod deformation measurement is proposed. An image processing algorithm for the implementation of the proposed system is also suggested. The inspection system is composed of a semiconductor laser module that emits a linear line beam, a high-resolution CMOS image sensor, a PC for acquiring and processing images, and a micro stage, which moves a nuclear fuel rod sample minutely within a 50 μm span. For this method, it is assumed that a nuclear fuel rod and the optical axis of the VT system used for observing the rod are vertically composed. If a laser line beam in the red spectrum (660 nm) is irradiated on the surface of the nuclear fuel rod at certain degree angle, a parabola-shaped pattern is imaged on the CMOS sensor. When the location of the nuclear fuel rod is varied minutely in the horizontal direction, the location of the parabola-shaped laser beam imaged on the CMOS sensor

moves upward and downward. If the incident angle of the laser line beam is 45 degrees or higher, the horizontal displacement of the nuclear fuel rod is converted into a vertical displacement of the nuclear fuel rod by a 1:1 ratio or larger. Accordingly, if the location of the laser beam is measured using a high-resolution CMOS image sensor and image processing technology, the deformation of the nuclear fuel rod can be inspected with high precision. In this paper, we describe image processing techniques that enable us to capture the image of a nuclear fuel rod on which a laser line beam is illuminated, pre-process it for noise elimination, and calculate the rod's degree of deformation. In addition, based on the incident angle of the laser line beam, a formula is derived that expresses the correlation between the displacement of a nuclear fuel rod and movement of the laser line beam imaged onto the CMOS sensor. An experiment conducted for the precise deformation measurement of a fuel rod sample with a crud formation is described. Finally, the resolution of the deformation measurement method proposed is compared to the conventional measurement criteria.

2. VISUAL INSPECTION OF THE NUCLEAR FUEL ROD

2.1 Inspection System

A conceptual diagram of the micro displacement measurement of the nuclear fuel rod is shown in Figure 1. In Figure 1, the VT (visual test) system is a high-definition CMOS imaging system. If a line beam emitted from a semiconductor laser diode is illuminated onto the

surface of a fuel rod at a certain angle (θ) based on the optical axis of the VT system, the laser line beam pattern on the surface of the fuel rod is displayed as a parabolic shape on the monitor of the VT system. It is assumed that displacement of the nuclear fuel rod, Δx , occurs along the optical axis of the VT system. In this case, the laser beam pattern displayed on the monitor of the VT system moves Δy in the vertical direction. When the displacement of the fuel rod in the front and rear directions is Δx , the displacement of the laser beam pattern in the upward and downward directions according to the horizontal movement of the fuel rod is Δy . The expression between these displacements and the incident angle of the laser line beam can be described as in Equation (1).

$$\tan \theta = \frac{\Delta x}{\Delta y} \quad (1)$$

That is, if it is assumed that the incident angle (θ) of the laser line beam is known, from the Δy measurement of the laser beam pattern, we can figure out the displacement of the fuel rod, Δx , in the horizontal direction. From Equation (1), it is apparent that the incident angle of the laser line beam, θ , is a critical variable for a high-precision measurement of the fuel rod displacement. When the incident angle of the laser line beam is 45 degrees, the Δy measurement value of the laser beam pattern is the same value as the displacement of the nuclear fuel rod. This can be expressed as Equation (2).

$$\Delta y = \Delta x, \quad \text{if } \theta = \pi/4 \quad (2)$$

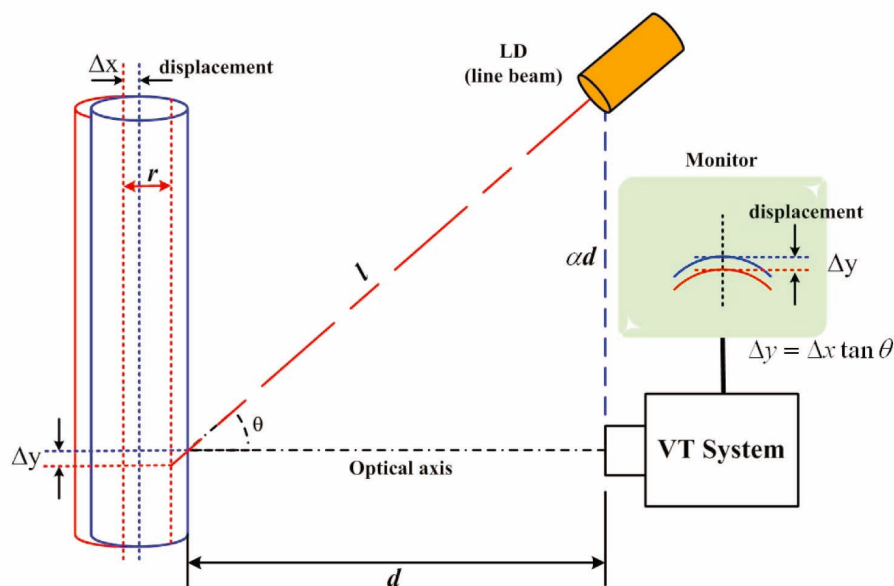


Fig. 1. Conceptual Diagrams of the Micro-displacement Measurement of a Fuel Rod.

To establish Equation (2), the semiconductor laser diode should be located at a height corresponding to the observation distance, d , between the VT system and fuel rod in the vertical direction based on the optical axis of the VT system, as shown in Figure 1. At this time, the distance, l , between the semiconductor laser diode and the laser beam spot on the surface of the fuel rod is expressed as Equation (3).

$$l = \sqrt{(\alpha d)^2 + d^2}, \quad \alpha = \tan \theta \quad (3)$$

If the incident angle of the laser beam is large, the resolution of the measurement is improved by $1/\alpha$. In this case, however, the position of the semiconductor laser diode should be α times higher than the distance between the fuel rod and the VT system. Therefore, the semiconductor laser diode has a high power performance, and sophisticated optics are required for collimating laser beam patterns over a long distance. A nuclear fuel rod that has been burned for more than one cycle in the reactor emits a high dose-rate gamma ray of approximately 3 kGy/h [3][4]. The CMOS image sensors cannot survive in high dose-rate gamma ray exposure environments of more than 100 Gy/h [5]. In such an environment, the observation performances of the CMOS image sensor severely deteriorate due to white speckle noise resulting from the gamma-ray radiation. In general, the width of the cooling water required for reducing the intensity of gamma rays with an energy level of 1 MeV to 1/10 of its original intensity is 66.04 cm [6]. This is denoted as one-tenth thickness of the gamma ray shield. Accordingly, to inspect a nuclear fuel rod precisely using a high-resolution CMOS image sensor, the sensor has to be protected from the high dose-rate gamma rays emitted from the neutron irradiated fuel rod. Using the gamma-ray shielding characteristic of cooling water, the VT of the nuclear fuel rod is conducted underwater. Also, the VT system should be located 2 m to 3 m away from the neutron irradiated fuel rod. If a semiconductor laser diode is located on the y axis of the VT system and the incident angle of the laser beam is 45 degrees, the distance between the laser diode and beam spot on the surface of the fuel rod is about 2.8 m to 4.2 m. An optical system that enables collimation of the divergence of a laser beam at a minimum level is also required. Also, the laser should have high output power. Crud formed on the surface of a neutron irradiated fuel rod is generally tinted black. The black tint reduces the reflection of the laser beam. In this paper, it is assumed that the semiconductor laser diode is not located on the y axis of the VT system, but at a location near the nuclear fuel rod. The location of the semiconductor laser diode is chosen based on its material characteristics. The CMOS image sensor used is made from Si, which belongs to group IV in the periodic table. Semiconductor laser diodes including LEDs are made from a GaAs element, which belongs to group III-V in the periodic

table. As a GaAs element has a higher energy band gap than Si, the electron-hole pair generation rate at the p/n junction of the GaAs resulting from the impingement of high-energy gamma rays on the semiconductor material is lower than that of the Si. Therefore, a semiconductor laser diode made from GaAs material is more hardened against radiation than a CMOS image sensor made from Si materials [7][8]. From the results of high dose-rate gamma ray irradiation experiments on LED devices, it is known that the semiconductor laser diode and additional optics that collimate the linear line beam have sufficient survivability in a high dose-rate gamma ray exposure environment of the VT test of a neutron-irradiated fuel rod. The VT inspection of 200 neutron-irradiated fuel assemblies loaded onto the reactor and burned during the operating cycle of the nuclear power plant should be carried out within approximately 3 days. The gamma ray dose-rate of a neutron-irradiated fuel rod is conservatively estimated to be 3 kGy/h. In this case, the laser diode is dosed with about 216 kGy of gamma rays based on the criteria of total irradiation dose (TID) during a VT inspection period of around 3 days. Based on the experimental results of the 4 kGy/h gamma irradiation test of the LED and power LED, which have the same physical structure as a semiconductor laser diode, we concluded that the semiconductor laser diode has sufficient survivability in such an intense gamma-ray radiation environment, although the laser diode is located within only 0.5 m of the neutron irradiated fuel rod for maintaining a minimum laser beam divergence. In these experiments, the LED and power LED were irradiated with gamma-rays at a dose-rate of 4 kGy/h for 2 to 72 hours. The electro-optical performance of the LED was evaluated on- and off-line. The LED and power LED operated normally after a 288 kGy dose and their electro-optical characteristic, luminance versus drive current, sustained good linearity [9][10].

2.2 Calculation of Resolution of the VT System

The resolution of the VT system was calculated using a notched ruler. Figure 2 shows the observed image of the fuel rod sample with a 9.66 mm diameter placed next to the ruler.

To calculate the resolution of the VT system, the line segments of the notch mark scale of the ruler were extracted. The slope and intercept of the line segment were also derived. From the line segments, the average slopes and intercepts were calculated. The resolution of the image sensor is the result of dividing the span between notched marks of the ruler by the average intercept value of the line segments. As shown in Figure 2, the span between notch marks of the ruler is 1 mm. 15 line segments were extracted. The average of the slope of each line is then expressed as Equation (4). The angle of the representative line segment of the 15 lines is expressed as Equation (5). The average intercept of each line is expressed as Equation

(6). From Equation (5) and (6), the pixel resolution is then calculated using Equation (7).

$$Slope_{avg} = \sum_{i=1}^n Slope_i / n, \quad n = 15 \quad (4)$$

$$line_{radian} = \arctan(Slope_{avg}) \quad (5)$$

$$Intercept_{avg} = \sum_{i=1}^{n-1} \frac{(Intercept_{i+1} - Intercept_i)}{(n-1)} \quad (6)$$

$$Pixel_{resolution} = \frac{Ruler_{span}}{Intercept_{avg} \times \cos(line_{radian})}, \quad Ruler_{span} = 1mm \quad (7)$$

Using Equation (7), the pixel resolution of the image sensor is calculated as $30.3689 \mu m$, as shown in Figure 2. This means that the Δx displacement of the fuel rod in the horizontal direction is $30.3689 \mu m$ when the laser beam pattern on the image sensor is moved upward or downward 1 pixel along the y axis.

2.3 Extraction of the Laser Line Beam Position

The position of the laser line beam is extracted from the observed image. In this paper, the laser line beam region is extracted using an image subtraction technique, which subtracts the fuel rod image (laser off) from the one overlaid with the laser beam pattern (laser on). Figure 3 shows the image processing algorithm for the

detection of the feature point of the laser beam pattern.

In Figure 4, the top-left is a fuel rod image acquired before laser beam illumination, and the top-right is an image taken after laser beam illumination. By subtracting the images taken before and after laser beam illumination, the region of the laser beam pattern is only displayed in the subtracted image. After the threshold process of the subtracted image, the region of the laser beam pattern is extracted as shown in the middle image of Figure 4. Here, the laser line beam, which is illuminated on the surface of the fuel rod at an incident angle of a certain degree, is observed as a parabolic shape with a certain thickness on the image sensor. Because the laser diode has a certain beam width and a certain divergence angle, the distances from the laser diode to the beam spots on the fuel rod surface on which the laser beam is reached are different. An ellipse model is derived using the contour coordinates of the parabola. The center of the ellipse model is taken as the feature of the deformed fuel rod. By ascertaining the feature position of the laser beam, the displacement of the nuclear fuel rod in the front and rear directions, that is, the deviation from the origin, which is the point at which the displacement does not occur, can be estimated. The vertical offset between the coordinates of the feature point and the origin is calculated. The offset is represented in numbers of pixels. To estimate the real displacement of the fuel rod, the numbers of pixels are replaced with the numbers of pixels multiplied by the resolution of the VT system. The contour shape is varied with the selection of the threshold value in the threshold process. The center of the ellipse modeled using the varied contour coordinates also varies. To minimize deviation in the detection of the laser beam pattern, the centers of the ellipse models are extracted several times using many contour shapes with the

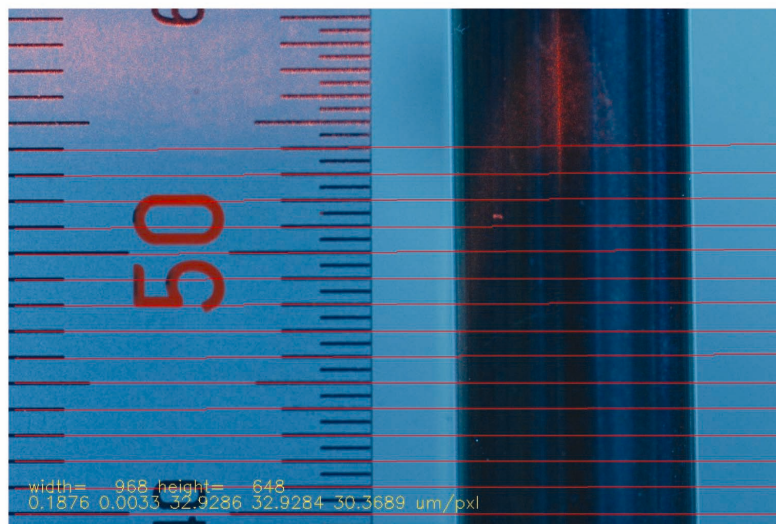


Fig. 2. Observation Image of a Fuel Rod with Crud.

selection of different threshold values. The centers of the ellipses are also averaged. The averaged center of the ellipse models is taken as the final feature of the deformed fuel rod. Figure 5 shows the variation of the center coordinates (y-axis) of the ellipse model with the threshold value.

To evaluate the linearity relationship between the variation of the laser beam position and the horizontal movement of the nuclear fuel rod, we investigated the

consistency of the detection of the laser beam position. The consistency of the detection of the laser beam position of a slightly declined fuel rod was also investigated.

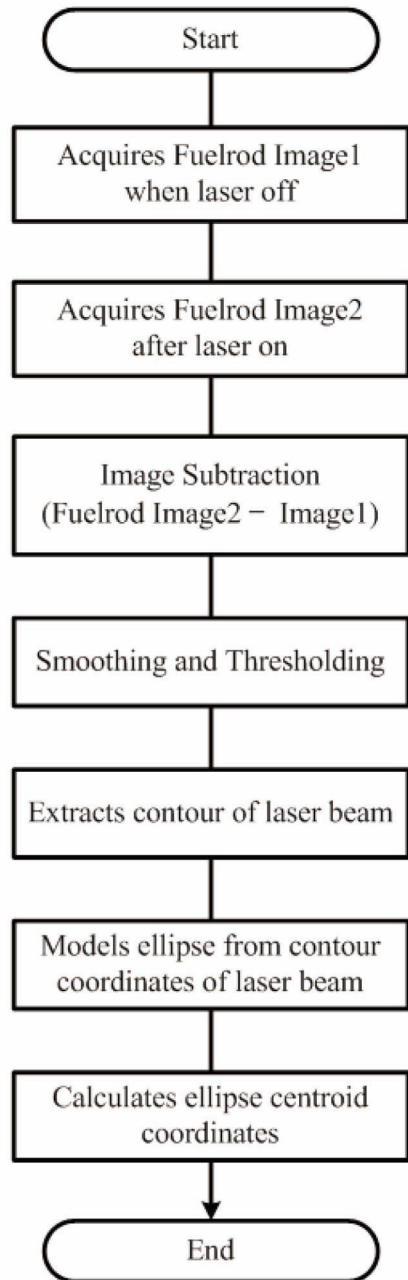


Fig. 3. A Flowchart of the Image Processing Algorithm for the Detection of the Feature Point of a Laser Line Beam.

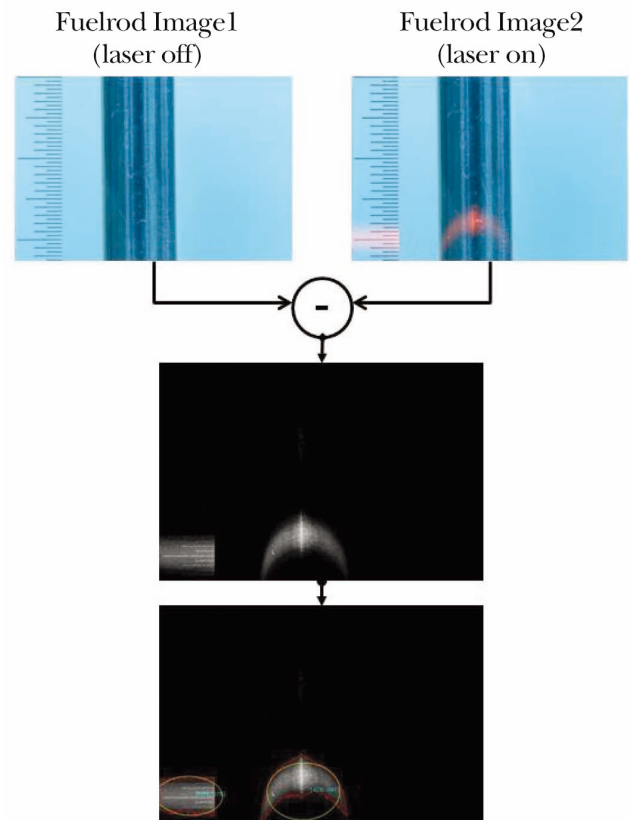


Fig. 4. A Laser Line Beam Area Extraction Using an Image Subtraction Method. (Before and After Laser Beam Illumination)

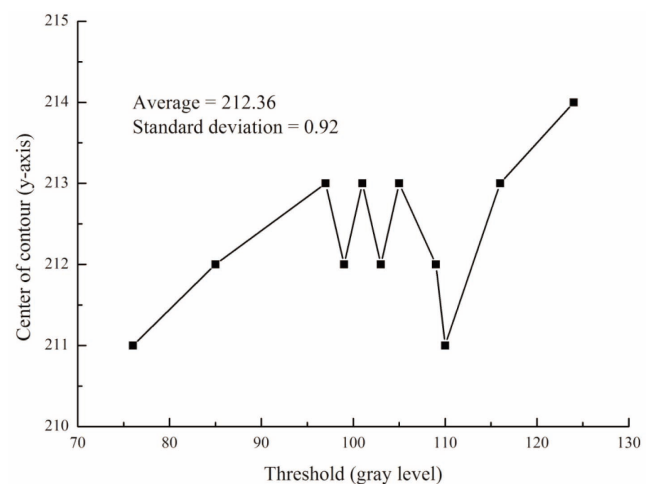


Fig. 5. Centers of the Ellipse Models with the Threshold Value Variations.

Figure 6 shows the linearity relationship between the variation of laser beam position detection and the horizontal movement of the nuclear fuel rod. From Figure 6, we estimate that the coherence between the position of the laser beam and the movement of the nuclear fuel rod is good.

3. EXPERIMENT AND RESULTS

As shown in Figure 7, a fuel rod sample on which crud is formed is moved in the front and rear directions at 0.1 mm steps using a micro-stage knob. The semiconductor

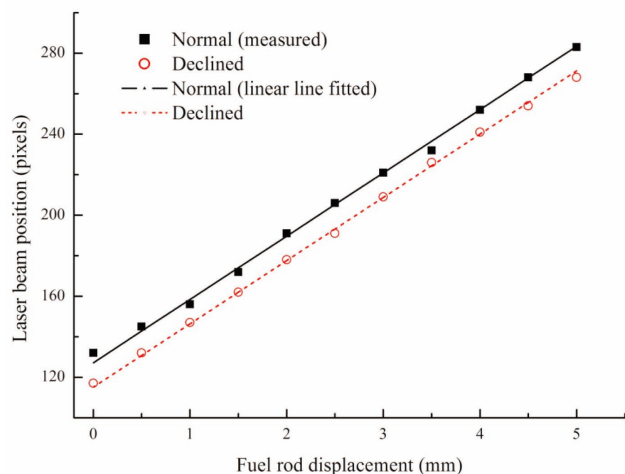


Fig. 6. A linearity Relationship Between the Position of the Laser Beam Detection and the Movement of the Nuclear Fuel Rod in the Horizontal Direction.

laser diode, which emits a linear line beam, is a Class IIb laser with a 20 mW output at a 650 nm wavelength.

If the incident angle θ of the laser beam is larger than 45 degrees, the displacement Δy in the vertical direction moves further upward or downward than the same displacement Δx in the horizontal direction. As displacement Δy in the vertical direction is larger, the resolution is enhanced and the measurement error is diminished. In this study, the resolution and error rate are analyzed for four incident angles of 45°, 60°, 70° and 80° for a 440 mm distance. When the VT inspection for the neutron-irradiated fuel rod is executed in the canal, which is the underwater transportation path for loading and unloading the nuclear fuel assembly in the reactor of the nuclear power plant during the overhaul period, the 440 mm distance is the allowable minimum clearance length between the fuel rod and VT system. For the four incident angles of the laser beam, the position of the fuel rod is moved toward the front or rear directions at 100 μm steps. The feature points of the parabola in the laser beam image are statistically analyzed according to variations in the movement of the fuel rod sample. The resolution is also derived by calculating the average value and standard deviation of the difference in pixel positions of the feature from the 100 μm step movements. Figure 8 is a graph analyzing the variation of feature points of the parabola in the laser beam image according to the displacement of the fuel rod toward the front and rear directions when the laser beam incident angles are 45°, 60°, 70° and 80°. In Figure 8, the x axis indicates the displacement of the fuel rod sample in the front and rear direction, and the y axis indicates the center point of the ellipse model in the laser beam image.

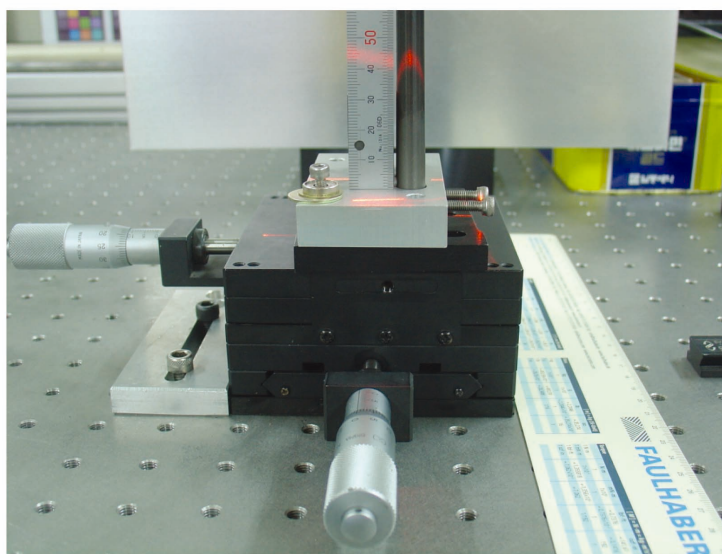


Fig. 7. Experimental Setup for Micro Movement of the Fuel Rod

Table 1 shows the relationship between the incident angle and the resolution of the displacement measurement. Assume that the incident angle of the laser beam is 60 degrees, as shown in Table 1. When the distance between the fuel rod and VT system is 440 mm, the semiconductor laser module is located at about a 760 mm vertical height from the optical axis of the VT system. If the fuel rod sample is moved $100\text{ }\mu\text{m}$ in the horizontal direction, the feature coordinates of the laser beam observed in the image sensor are represented by 4.68 pixels as an average value. If the laser beam position is α pixels deviated from the origin in the observed image of the nuclear fuel rod, real displacement of the nuclear fuel rod, f_d , is expressed as Equation (8).

$$f_d = \frac{100\text{ }\mu\text{m}}{\alpha[\text{pixels}]} \quad (8)$$

When the incident angle of the laser beam is 80° , α is 15.22 as shown in Figure 8. From Equation (8), the detection resolution of the nuclear fuel rod displacement is about 6.57 mm. This measurement resolution should

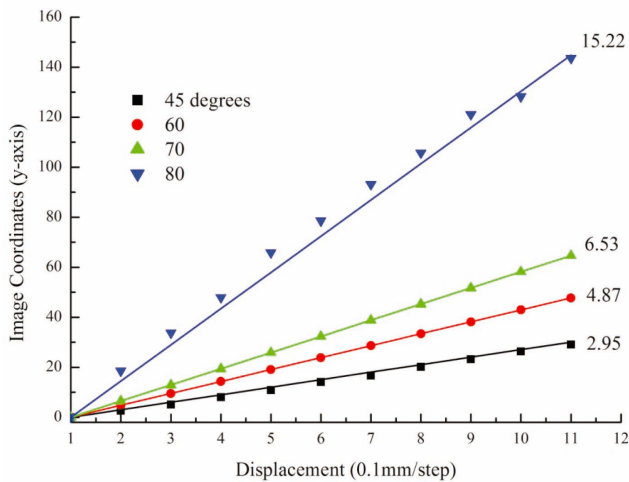


Fig. 8. Laser Beam Positions According to the Back and Forth Displacement of the Fuel Rod.

Table 1. Displacement Resolution of the Fuel Rod Due to the Incident Angle of the Laser Line Beam.

Incident angle of laser line beam	45°	60°	70°	80°
Resolution	0.2mm	0.1mm	0.1mm	0.05mm
Average [pixels]	5.82	4.68	6.38	7.18
Standard Deviation	0.64	0.76	0.84	1.59

be enhanced more precisely if the cell size of the CMOS image sensor is reduced by 2 to 3 times, to $0.4 \sim 0.7\text{ }\mu\text{m}$, which is the wavelength spectrum of visible light.

4. CONCLUSION

In this paper, a high precision inspection method for nuclear fuel rod deformation is proposed. For this method, a semiconductor laser diode that radiates a linear beam in the shape of a straight line and a high-resolution CMOS image sensor are used. When a laser line beam is irradiated on the surface of a fuel rod at 45 degrees or higher, based on the angle between the optical axis of the image sensor and the fuel rod, the displacement of the fuel rod in the horizontal direction is observed by the image sensor as equal to or larger than the displacement in the vertical direction. A laser line beam irradiated on the surface of a nuclear fuel rod at a certain angle is observed as having a parabolic shape with a certain thickness on the image sensor. The parabola, which appears on the image sensor, is modeled into an ellipse. The vertical offset of the feature point of the nuclear fuel rod according to the displacement of the feature point in the horizontal direction is derived. Based on the experimental results for a nuclear fuel rod sample with a crud formation, an inspection resolution of $35\text{ }\mu\text{m}$ was achieved using the proposed method. The precision of the inspection resolution is improved by more than 4 times from the original inspection resolution of $150\text{ }\mu\text{m}$, which is the conventional measurement criteria required for the deformation of a neutron irradiated fuel rod. Currently, a VT inspection is conducted using a mono camera. For a precise discrimination of the prominence or depression of a micro displacement, such as a dent, the VT inspection for a neutron-irradiated fuel rod using a single CCD and CMOS camera relies greatly on the inspector's skill. As a semiconductor laser diode is robust under a high dose-rate gamma ray radiation environment, it should be positioned close to the neutron-irradiated fuel rod. Hence, it is expected that high precision measurements for the displacement of nuclear fuel rods may be accomplished using the method suggested in this paper.

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