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Development and Validation of a 3D Full-Length Fuel Rod Surface Measurement System

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1. Introduction

Nuclear fuel assemblies experience fluid-induced vibrations due to the coolant flow surrounding them. The fuel rod supported by springs and dimples of the spacer grid, undergoes fretting wear caused by the vibration. Fretting wear of the fuel rod affects the safety and integrity of nuclear fuel; therefore, the wear characteristics must be evaluated.

At KEPCO NF (KNF), the evaluation of fuel wear characteristics is conducted based on the results of long-term wear tests during the fuel development process [1]. The long-term wear test is performed using a test fuel assembly, specifically manufactured to replicate an actual fuel assembly, by inducing fluid-induced vibrations under controlled hydraulic conditions for 500 hours. Wear characteristics are evaluated based on the measurement results of wear on the fuel rod specimens after the long-term wear test.

Innovative small modular reactor (SMR) nuclear fuel is being developed, and a long-term wear test is planned for wear evaluation. However, conducting full-contact measurements for all fuel rods is time-consuming. To enable precise and rapid measurement of the worn surfaces on fuel rod specimens, a three-dimensional full-length surface profilometry system based on a chromatic confocal line sensor [2] has been developed. While the sensor itself is a model commonly used in surface profilometry systems, the operational system of the equipment has been specifically designed to enable rapid full-length measurement of a fuel rod, which may influence measurement results due to the behavior of the equipment. Therefore, validation tests were conducted to assess the surface measurement performance of this newly developed system.

For equipment validation, various characteristics were examined, including sensor-specific properties, automatic position searching and scanning, and system vibrations. This paper provides a brief introduction to the equipment and focuses primarily on the validation results of its critical performance parameter: the ability to measure surface defects on the fuel rod.

2. 3D full-length rod surface measurement equipment

The chromatic confocal sensor (CCS) is a non-contact 3D surface measurement method that utilizes chromatic aberration. Light from a white light source is split into monochromatic wavelengths by a lens, with each wavelength having a different focal distance. Only the light corresponding to the surface’s distance passes through the pinhole and is captured by a charge-coupled device (CCD). The position difference on the CCD allows identification of the passing wavelength, which is then used to determine the surface distance.

As shown in Fig. 1, the chromatic confocal line sensor differs from the point scan method, described in the principle above, by simultaneously measuring multiple points distributed along a specific length. Additionally, compared to a standard single-point sensor, it has relatively lower resolution but offers a significant advantage in measurement speed.

Fig. 2 shows the 3D full-length fuel rod surface measurement equipment. Its performance specifications are listed in Table 1. The system is capable of measuring the entire surface of a fuel rod and can automatically move to specific locations, such as spacer grid contact points, for precise measurements. The measurement results are processed using dedicated surface analysis software.

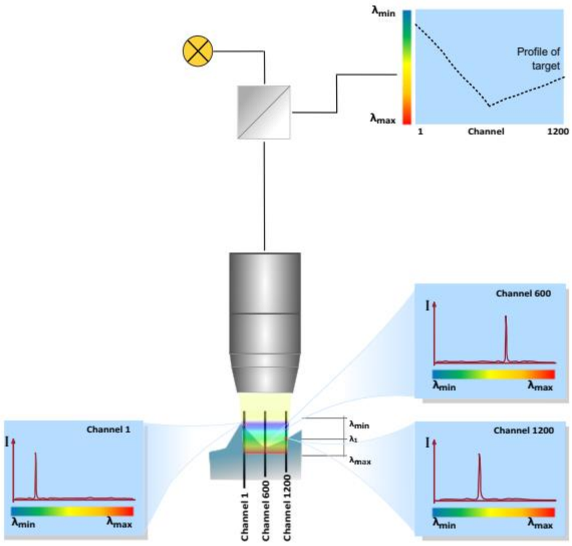

Fig. 1 Principle of Chromatic Confocal Distance Measurement [2]

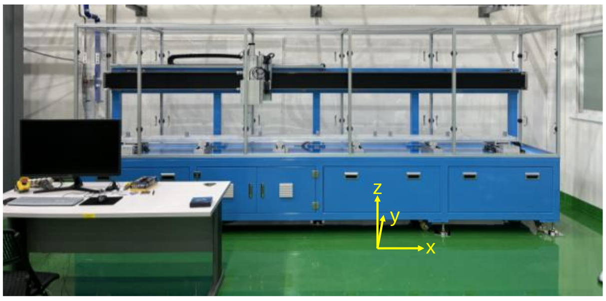

Fig. 2 3D full-length rod surface measurement equipment

Table 1 Specifications of 3D full-length rod surface measurement equipment

Measuring range (X, Y, Z)	(4 000, 4.42, 2.5) mm
Resolution (X, Y, Z)	(4, 4, 0.2) μm
Linearity	2 μm
Scan rate	7930 Hz

3. Equipment validation

To validate the measurement system, two types of specimens were used. The first was a reference specimen with artificial defects on the cladding surface, precisely fabricated through machining. The dimensions of these defects—length, width, and depth—were measured and certified by an accredited calibration institute. The second was a worn cladding specimen obtained from a wear test, which contained surface defects caused by fretting wear.

The reference specimen was measured using the newly developed system, and the results were compared with the certified values. As shown in Table 2, the relative error was within 5%, confirming the accuracy of the system.

Table 3 presents the measurement results of the worn specimen. Since obtaining certified values for worn specimens is challenging, the results were compared with those obtained using another 3D surface measurement system. This comparative system employs a point-scan chromatic confocal method and is designed for measuring small-scale specimens. Although it has higher resolution and precision than the newly developed system, it is significantly slower and has a limited measurement range. The relative error in maximum wear depth and wear volume measurements was within 5%, indicating that the new system can accurately and efficiently measure wear across the entire fuel rod after long-term wear testing.

Table 2 Measurement results of reference specimen

	Result [μm]	Ref.* [μm]	Error (%)
Length	1.013	0.995	1.8
With	1.398	1.387	0.8
Depth	8.066	8	0.8

* Certified value by an accredited calibration institute

Table 3 Measurement results of the wear specimen (normalized)

	Result	Ref.*
Wear volume	1.037	1
Max. wear depth	0.952	1

* Measured by the 3D profilometer of point type CCS

4. Conclusions

A 3D full-length surface measurement system was developed to evaluate fuel rod wear after long-term fretting wear tests. Validation tests were conducted to assess performance of the equipment. Measurements from both reference specimens with artificial defects and worn specimens from wear tests were compared with certified values and results from a high-precision point-scan system, respectively. The comparison confirmed that the newly developed system can accurately measure fretting wear.

Future work will involve repeated measurements to evaluate uncertainty and further enhance the validation level of the equipment. This system is expected to be utilized not only for the long-term wear evaluation of innovative SMR nuclear fuel but also for control rod wear assessment.

REFERENCES

[1] KNF-TR-MTA-21001, Nuclear Fuel Mechanical Design Manual, 2021
[2] User manual, PRECITEC

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