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Experimental Study on Vibration Characteristics of i-SMR Fuel Cladding

Han-Sang Woo*, Jinseon Kim, Kyoung-hong Kim, Youngik Yoo, Donggeun Ha, Joonkyoo Park
Kepco Nuclear Fuel, #242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author: dngkstkd@knfc.co.kr*

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1. Introduction

The nuclear industry has been promoting the development of the i-SMR(Innovative Small Modular Reactor) to achieve carbon neutrality through enhanced safety and economic efficiency. The i-SMR adopts innovative design concepts including boron-free operation, 24-month long-cycle operation, and a 0.5 g seismic design. However, in the high-speed flow environment of the coolant, the fuel cladding is exposed to FIV(Flow-Induced Vibration), which can cause GTRF(Grid-To-Rod Fretting), potentially compromising the integrity of the nuclear fuel [1].

In this study, vibration tests were conducted to evaluate the dynamic characteristics of i-SMR fuel cladding under various support conditions and burnup-dependent cell sizes [2]. The data reliability according to the test method was compared, and the influence of grid the support force on resonance frequencies and mode shapes was analyzed [3]. These findings aim to provide fundamental data for i-SMR fuel design and the verification of vibration analysis models.

2. Test

2.1. Test Equipment

The i-SMR fuel consists of cladding tubes filled with pellets, spacer grids(top, intermediate, mixing, bottom), and guide tubes. Fig. 1 shows the fuel rod vibration test equipment. The test setup comprises Frame, impact hammer, and the data acquisition and analysis system.

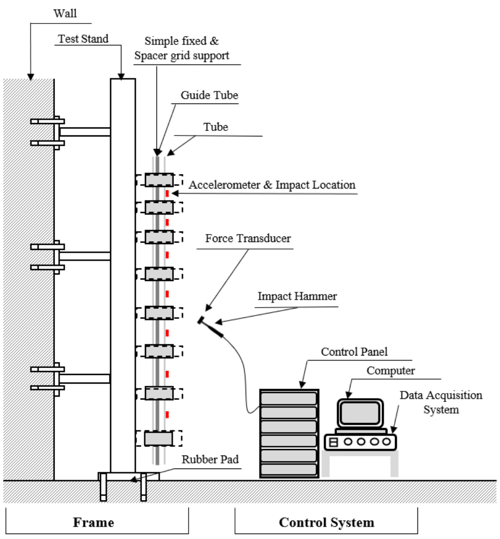
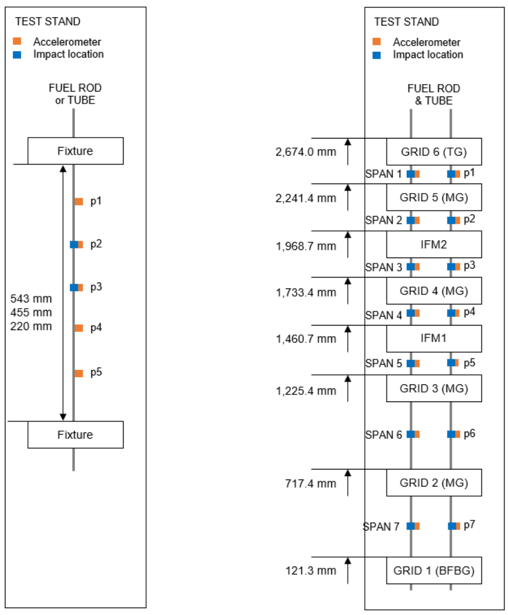


Fig. 1 Fuel rod vibration test equipment

2.2. Test Configuration and Method

The test specimen configurations were divided into simple fixed support condition and spacer grid support condition, as shown in Fig. 2. The 6×6 spacer grid specimens were fabricated based on the HANA-6 spacer grid. These were either used as "as-built" cells to simulate BOL(Beginning Of Life) condition or modified by expanding cell sizes to simulate EOL(End Of Life) condition.

To determine the optimal procedure for fuel cladding vibration testing, a comparison was conducted between the SSVM(Sine Sweep-based Vibration Method) and the IHVM(Impact Hammer-based Vibration Method). The FRFs(Frequency Response Functions) and mode shapes were derived for each method, and resonance frequencies were analyzed based on the support conditions. The test conditions for the fuel rod vibration are summarized in Table I.



(a) Simple fixed (b) Spacer grid
Fig. 2 Configuration for test specimen

Table I: Test conditions for fuel rod vibration

<table>
<tr><th>Test method</th><th>Support condition</th><th>Vibration location</th><th>Vibration method</th></tr>
<tr><td>SSVM</td><td rowspan="2">Simple fixed</td><td>p3</td><td>Sine-sweep (0.3 N, 1-2,500 Hz)</td></tr>
<tr><td rowspan="2">IHVM</td><td>p2, p3</td><td rowspan="2">Impact</td></tr>
<tr><td>Spacer grid</td><td>p1 ~ p7</td></tr>
</table>

2.3. Test Results

Figs. 3 through 6 show the FRFs and mode shapes obtained from the SSVM and IHVM, respectively. In the SSVM, the mass and stiffness of the stinger-jig assembly exerted a greater influence on the results than those of the fuel rod, limiting the identification of resonance frequency. In contrast, the IHVM clearly identified resonance frequencies and mode shapes, proving more suitable for analyzing the vibration characteristics of the cladding. However, it was noted that resonance frequencies might not be identified if the impact location is near dead points, highlighting the importance of selecting the proper impact location.

According to the results of the simple fixed support condition, a consistent trend was observed where the resonance frequency increased as the support distance decreased. In the spacer grid support condition, only the first mode was identifiable due to the reduction in support force. Specifically, the EOL conditions resulted in overall lower resonance frequencies compared to BOL conditions due to the weakened support force.

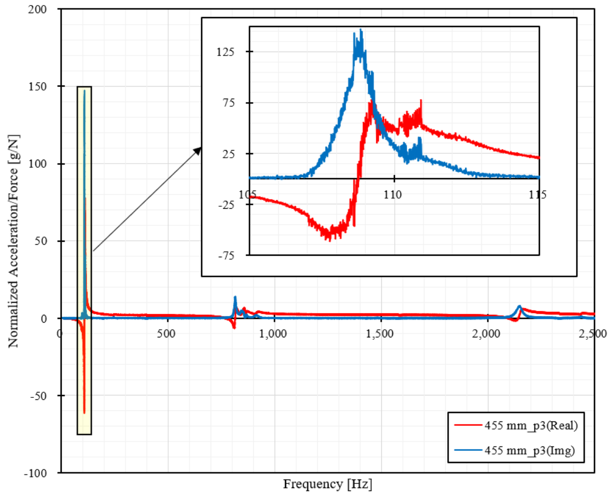


Fig. 3 FRFs(SSVM)

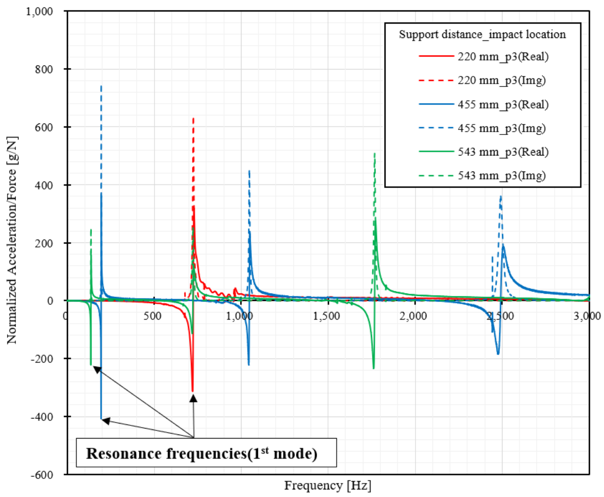
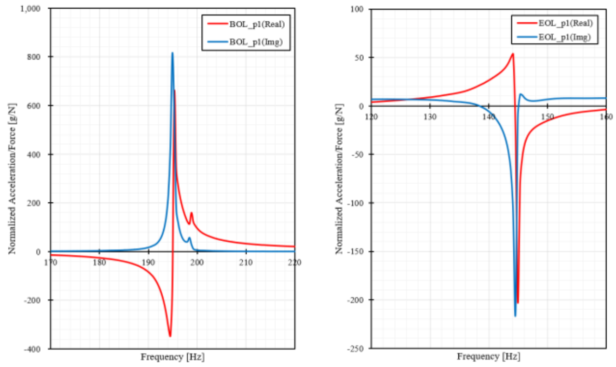
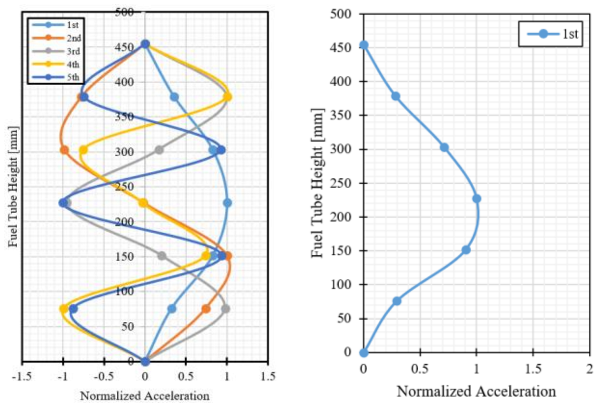


Fig. 4 FRFs(IHVM, simple fixed)



(a) BOL (b) EOL

Fig. 5 FRFs(IHVM, spacer grid)



(a) Simple fixed (b) Spacer grid

Fig. 6 Mode shapes(IHVM)

3. Conclusion

The conclusions of this research are as follow:

(1) While the SSVM experienced data distortion due to the mass and stiffness interference of the testing apparatus(Stinger-Jig), the IHVM demonstrated high reliability in identifying the resonance frequencies and mode shapes of the fuel cladding.

(2) The IHVM confirmed a consistent trend of increasing resonance frequencies as the support distance shortened. In particular, the EOL condition yielded lower resonance frequencies compared to the BOL condition due to weakened support force, suggesting that the support force is a critical variable determining the vibration characteristics of the cladding.

(3) It was confirmed that selecting the optimal impact location is crucial for accuracy of IHVM results, as resonance frequencies may not be identified if the impact occurs near a dead point. Therefore, multiple impact locations must be considered to ensure a comprehensive evaluation of the fuel cladding vibration characteristics.

Future research will focus on a comparative analysis between the experimental and numerical results, specifically incorporating the effects of surrogate pellets designed to simulate the internal mass of actual fuel pellets.

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