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On Analyzing Seismic Behaviors of Dynamic Absorber-applied Nuclear Power Plant Piping According to Several Design Methods

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1. Introduction

The secondary structures of nuclear power plants (NPPs) play a crucial role in ensuring the safe operation of the NPPs and need to function reliably even in the event of beyond-design basis earthquakes (BDBEs). These secondary structures include components such as piping systems and electrical cabinets. In particular, the piping system performs essential functions related to cooling, electrical, and instrumentation. Therefore, this study utilized dynamic absorbers (DAs) to control excessive dynamic motion and maintain the plant's stable operation under earthquake events. DA is a device attached to a structure that absorbs vibrational energy at a specific frequency and reduces the structure's dynamic response. It consists of a spring, a damper, and a mass. The design of a DA requires determining its stiffness and damping ratio In this study, several existing design equations were referenced to compare and analyze seismic performance. Additionally, the geometric mean of these equations was employed to design and further utilize the dynamic absorbers.

2. Methods and Results

This study used a numerical model established and validated by Kwag et al. [1], based on shaking table test results of actual piping in NPPs. Furthermore, Kwag et al. [2] conducted shaking table tests with and without the DA and validated the numerical model accordingly.

2.1 Target Piping Model

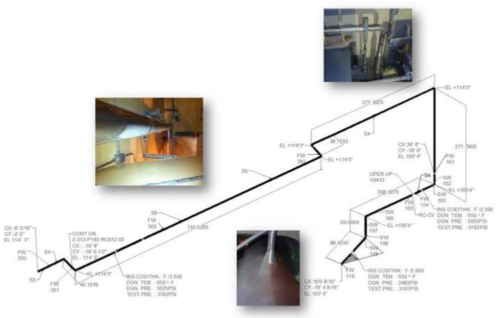

Fig. 1. ISO drawing and main part shapes of target piping [2]

The target piping is installed in the containment building of Shin-Kori Unit 2 and is composed of stainless steel pipes. The diameters are 2 inches and 3 inches, and the total length of the piping is 17.3 meters [2] (refer to Fig. 1). This study aimed to design a DA device to control the response at the primary fundamental mode frequency of the target piping. The primary fundamental mode frequency of the target piping is 2.02 Hz, and the focus is on controlling the EW direction. Fig.2 shows the first mode shape of the target piping model.

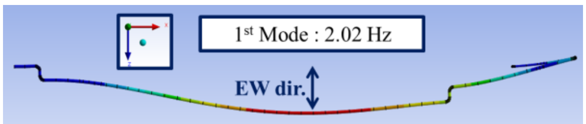

Fig. 2. Target piping model 1st mode shape

2.2 Seismic Input Motions

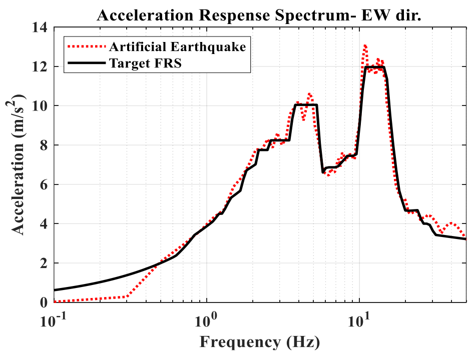

Fig. 3. Input acceleration response spectrum (EW dir.)

The artificial floor earthquake motions used as input for the shaking table test were generated based on the target floor response spectra (FRS) specified in USNRC 1.60. These artificial earthquake motions were applied in the EW (East-West) and NS (North-South) directions. Fig. 3 and Fig. 4 illustrate the 5% damping ratio response spectra for the EW and NS directions, respectively. Additional input motions were used to verify further and analyze the numerical model's behavior. However, this content is not included in the current paper.

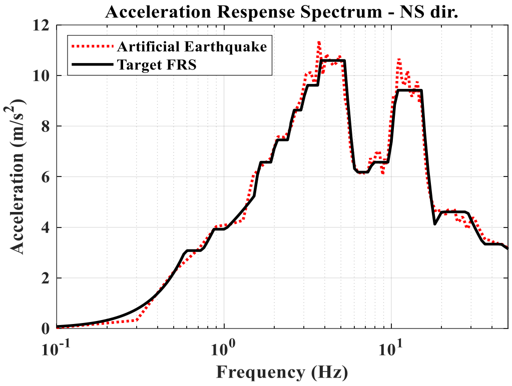

Fig. 4. Input acceleration response spectrum (NS dir.)

2.3 DA Design Values

Selecting the mass, optimal frequency ratio, and optimal damping ratio is essential to design a DA. In this study, the mass of the DA was set to 16 kg to avoid significantly affecting the behavior and mode frequencies of the overall piping system. Additionally, the optimal frequency ratio and optimal damping ratio were determined based on existing research by Den Hartog [3], Warburton [4], Sadek et al. [5], and Leung and Zhang [6]. Furthermore, this study derived the design values using the geometric mean of these equations to design the DA and compared it with existing equations. Table I summarizes the design values obtained through this methodology, focusing on the optimal frequency and damping ratios.

Table I: Details of the DA design values

	f_{opt}	ξ_{opt}
Den Hartog [3]	0.945	0.143
Warburton [4]	0.932	0.118
Sadek et al. [5]	0.934	0.281
Leung and Zhang [6]	0.905	0.117
Geometric mean	0.929	0.153

2.4 Comparison of Acceleration Response Spectrum

In this study, DA devices designed using different methodologies were attached to the numerical model to compare and analyze the piping responses. Fig. 5 shows the acceleration response spectrum graph of the piping in the EW direction with a 5% damping ratio at the DA installation location. The maximum acceleration response of the piping without the DA was observed around 2.1 Hz. As shown in Fig. 5, the response at this frequency was significantly reduced for the piping with the DA installed. In particular, the DA designed using the Warburton [4] equation achieved the greatest reduction in acceleration, recording 26.3 m/s^2, while the Sadek et al. [5] equation resulted in the smallest reduction, with a recorded value of 35.8 m/s^2. The geometric mean model proposed in this study reduced the response amplitude to 28.7 m/s^2. This phenomenon can be attributed to the fact that a larger damping ratio limits the motion of the mass (refer to Table I).

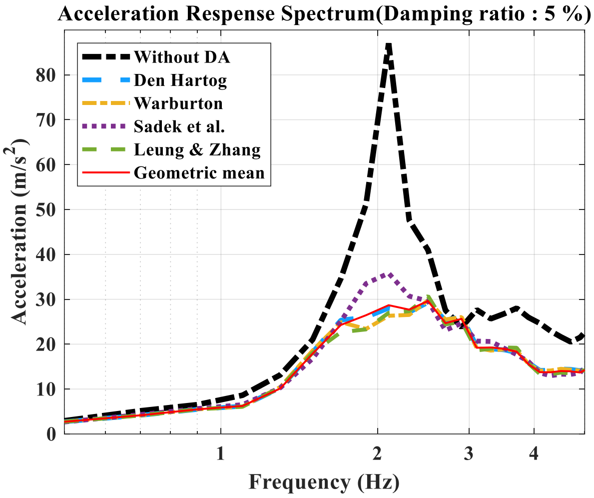

Fig. 5. Acceleration response spectrum comparison at the DA installation location (damping ratio: 5%)

3. Conclusions

In this study, the DA was used to reduce the seismic response of the piping, a major secondary structure in NPPs. Specifically, the equations from existing researchers and a model derived from the geometric mean of these equations were used to assess performance. As a result, the DA designed using the geometric mean model reduced the piping's acceleration response by approximately 67.8% at 2.1 Hz. The Warburton [4] equation, which most effectively controlled the piping response, reduced the acceleration response by about 69.8%, showing performance similar to that of the geometric mean model. This geometric mean model was the second most effective in controlling the amplitude response. When designing the initial DA, it is not straightforward to derive design values by specifying a single methodology. Therefore, when designing a DA, a robust result might be acquired by using the geometric mean model presented in this study to set the initial values. This is because it provides robust values that encompass the characteristics of various methodologies by averaging them (i.e., this approach's design value would not lie in two extremes of the best and the worst that we do not know beforehand. Future studies aim to evaluate the performance of DA, which is designed using the geometric mean based on a model that considers the randomness of earthquakes and the uncertainties associated with earthquakes and materials. In addition, since dynamic absorbers are effective in reducing responses at specific frequencies, research will also focus on applying *n* dynamic absorbers to mitigate not only the primary mode response but also responses in other significant modes.

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