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Constructing a digital twin for estimating the response and load of a piping system subjected to seismic and arbitrary loads

Dongchang Kim [1a], Gungyu Kim [1b], Shinyoung Kwag [*2] and Seunghyun Eem [**1]

[1] *School of Convergence & Fusion System Engineering, Major in Plant System Engineering,*
Kyungpook National University, 2559 Gyeongsang-daero, Sangju, 37224, Republic of Korea
[2] *Department of Civil and Environmental Engineering, Hanbat National University,*
125 Dongseo-daero, Yuseong-gu, Daejeon, 34158, Republic of Korea

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Abstract. In recent years, technological developments have rapidly increased the number of complex structures and equipment in the industrial. Accordingly, the prognostics and health monitoring (PHM) technology has become significant. The safety assessment of industrial sites requires data obtained by installing a number of sensors in the structure. Therefore, digital twin technology, which forms the core of the Fourth Industrial Revolution, is attracting attention in the safety field. The research on digital twin technology of structures subjected to seismic loads has been conducted recently. Hence, this study proposes a digital twin system that estimates the responses and arbitrary load in real time by utilizing the minimum sensor to a pipe that receives a seismic and arbitrary load. To construct the digital twin system, a finite-element model was created considering the dynamic characteristics of the pipe system, and then updating the finite-element model. In addition, the calculation speed was improved using a finite-element model that applied the reduced-order modeling (ROM) technology to achieve real-time performance. The constructed digital twin system successfully and rapidly estimated the load and the point where the sensor was not attached. The accuracy of the constructed digital twin system was verified by comparing the response of the digital twin model with that derived by using the load estimated from the digital twin model as input in the finite-element model.

Keywords: digital twin; finite element model; real-time; reduced-order modeling (ROM); topography prognostics and health monitoring (PHM)

1. Introduction

Recently, the demand for cloud-based platforms has increased, and the Internet of Things (IoT), artificial intelligence (AI), and big data technologies have developed owing to improved computer performance and the advent of the Fourth Industrial Revolution. Therefore, the need for improvements in productivity, economy, and safety is increasing in various industrial fields (Hyun *et al.* 2017, Sorooshian and Panigrahi 2020, Lee 2021). Digital twin technology is attracting attention in meeting this demand (Oh *et al.* 2020, Shin and Park 2020, Nam *et al.* 2020). Digital twin technology implements actual equipment and space in a virtual world (Rassheed *et al.* 2020), and it is economical because it can save time and money through virtual simulation without experiments that are difficult to perform owing to high costs and produces results similar to actual experiments. In addition, structures that apply digital twin technology can predict the future, lead to efficient operation, quality improvement, and maintenance, and aid decision-making (Hwang *et al.* 2020).

Safety and health monitoring of structures and equipment is essential for industries (Aivaliotis *et al.* 2019, Ye *et al.* 2019). However, installing a large number of sensors in structures and equipment for safety and health management is uneconomical. In addition, it is difficult to install sensors in some locations of the structures, making it difficult to accurately measure the data. Digital twin technology is being utilized to solve this problem. Digital twin technology in the industrial field constructs a virtual system that operates identically to the target object by utilizing the data measured by sensors installed in the actual equipment (Cho *et al.* 2021, Oh *et al.* 2020).

The damage to structures has been increasing due to high-intensity earthquakes recently (UNDRR 2020, Setyogroho *et al.* 2022, Li *et al.* 2022). Accordingly, the research on the digital twin system for the safety evaluation of structures subjected to seismic loads is being actively conducted (Lin *et al.* 2021, 2022, Levine and Spencer 2022, Rabiepour *et al.* 2022). However, the research on the digital twin system of structures that simultaneously considers the seismic load and the arbitrary load such as wind and shock is insufficient. In addition, the knowledge of the accurate load applied to the equipment during actual operation is adequate for maintenance (Moi *et al.* 2020). Therefore, a digital twin system for estimating pipe responses and pipe

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*Corresponding author, Associate Professor,
E-mail: skwag@hanbat.ac.kr

**Co-corresponding author, Assistant Professor,
E-mail: eemsh@knu.ac.kr

[a] Graduate Student, E-mail: kdch2021@knu.ac.kr

[b] Graduate Student, E-mail: gyungyu819@knu.ac.kr

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loads derived in real time by receiving seismic and arbitrary loads was proposed in this study. The digital twin system of the pipe system reflects the dynamic characteristics being tested through model updating, and the pipe system response and load can be estimated in real time using reduced-order modeling (ROM). The constructed digital twin system is verified by comparing the responses of the numerical model.

2. Constructing the digital twin of a pipe system

The digital twin system estimates the response of unmeasured points and arbitrary loads in real time for pipe systems simultaneously subjected to seismic and arbitrary loads. The digital twin system, a numerical model that can express the behavior of the pipe system, was established to construct the digital twin system. A ROM was developed by using the numerical model to estimate the response of the pipe system in real time. First, ROM estimates the response where the acceleration sensors are attached with only the seismic load applied. The difference between the response obtained from ROM and sensors will be calculated and used for the estimation of arbitrary load. Finally, the response of the interested (unmeasured) points in the pipe system can be estimated by applying the estimated arbitrary load and seismic load into the ROM.

2.1 Target pipe system

The target pipe was utilized by modifying the pipe shape used in the Metallic Component Margins under High Seismic Loads (MECOS) benchmark hosted by OECD-Nuclear Energy Agency (NEA) (NEA 2018). The target pipe used for constructing the digital twin system is illustrated in Fig. 1. It was fabricated using a 3D printer using PLA Pro as the material. The thickness, inner diameter, outer diameter, and overall size of the pipe system are $1\ \mathrm{mm}$, $4\ \mathrm{mm}$, $6\ \mathrm{mm}$, and $100\ \mathrm{mm} \times 100\ \mathrm{mm} \times 50\ \mathrm{mm}$, respectively

The pipe system was installed on a shaking table to simulate the seismic load, and an acceleration sensor was attached to it and the shaking table to measure the seismic load and responses of the pipe system. The actuator applies an arbitrary load in the diagonal direction to the pipe system. The location of the acceleration sensor attached to the pipe system and the experimental setup are shown in Fig. 2. The acceleration data measured by the sensors were acquired using an NI DAQ-9174 device.

2.2 Finite-element model of the pipe system

The finite-element model for constructing a digital twin system of the pipe system using ANSYS Mechanical APDL is shown in Fig. 3 (Thompson and Thompson 2017). The initial values of the material property of the pipe system are: elastic modulus = $4 \times 10^9\ \mathrm{N/m^2}$, density = $1{,}100\ \mathrm{kg/m^3}$, and Poisson's ratio = 0.3. The finite-element model determined the natural frequency and mode shape through modal analysis. Table 1 lists the effective mass and the natural frequencies of the three lower modes of the finite-element model. The behavior of the first and second modes obtained from the finite-element models in the Z-axis and X-axis directions depend on the squared mass of the pipe system shown in Fig. 1. The mode shape is illustrated in Fig. 4.

Simulations of the digital twin system of the pipe system should closely replicate the pipe system behavior.

(a) Target pipe (b) Target pipe modeling

Fig. 1 Target pipe used for constructing the digital twin system

(a) Top view (b) 3D view

Fig. 2 Experimental setup

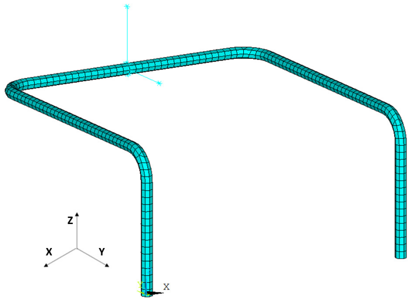
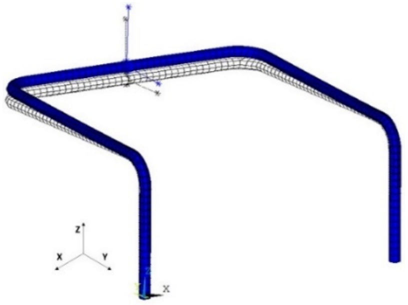


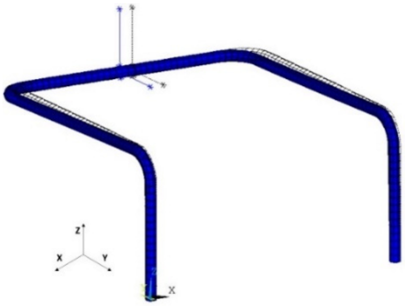
Fig. 3 Finite-element model of the pipe system

Table 1 Eigenvalue analysis using APDL

	Natural frequency from the finite-element model	Effective mass		
		X-Dir	Y-Dir	Z-Dir
Mode 1	10.330 Hz	0%	4.33%	89.84%
Mode 2	16.827 Hz	96.50%	0%	0%
Mode 3	43.788 Hz	0%	88.44%	4.81%



(a) 1st mode shape



(b) 2nd mode shape

Fig. 4 Mode shapes from the finite-element model

Therefore, the model was updated based on the data measured by the sensor attached to the pipe system by applying a random signal to the shaking table. The model was updated according to the procedure shown in Fig. 5 (Cho 2019, Tian *et al.* 2017).

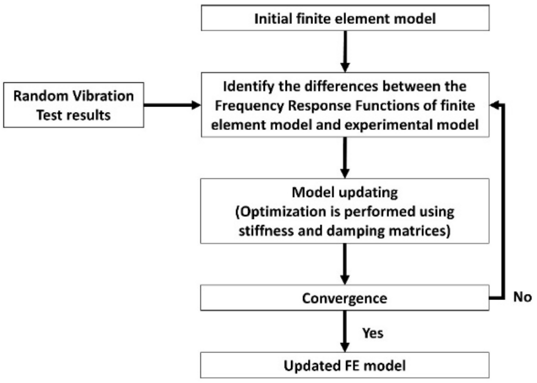


Fig. 5 Procedure for updating the model

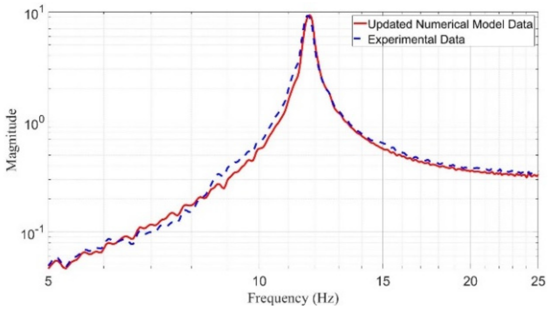


Fig. 6 Comparison of the frequency response functions of the pipe system and finite-element model used in the digital twin

Using the random vibration experiment, the first natural frequency of the pipe system was a measured to be 11.75 Hz. The optimal stiffness and damping matrices were derived using the Nelder-Mead simplex algorithm such that the frequency response functions of the pipe system and the finite-element model utilized in the digital twin were similar. The corresponding results of the two frequency response functions are shown in Fig. 6.

2.3 Applying the Reduced-Order Modeling (ROM) technique for constructing the digital twin model

The digital twin system of the pipe system proposed in this study estimated the pipe system responses and the load acting on the pipe system in real time. However, the finite-element model constructed in Section 2.2 had difficulties in estimating the real-time responses and load owing to the many degrees of freedom (DOFs). Therefore, the Craig-Bampton (CB) method was used to build the reduced-order model of the pipe system to improve the calculation speed (Craig and Bampton 1968). The CB method has the advantage of effectively reducing the model by utilizing a limited number of eigenmodes. Because some DOFs are preserved even after model reduction, direct comparison with actual measured deformation data is possible. The equation of motion for the model given in the CB method is expressed as

$$\begin{pmatrix} M_s & M_c \\ M_c & M_b \end{pmatrix}\begin{pmatrix} \ddot{u}_s \\ \ddot{u}_b \end{pmatrix} + \begin{pmatrix} K_s & K_c \\ K_c & K_b \end{pmatrix}\begin{pmatrix} u_s \\ u_b \end{pmatrix} = \begin{pmatrix} 0 \\ f \end{pmatrix} \tag{1}$$

The subscripts s, c, and b denote substructures, couplings, and boundary interfaces, respectively. Instead of directly processing the complex actual model, the CB method generates a reduced-order model and computes the eigenvalues of substructures partitioned into smaller substructures.

$$K_s^j \phi_k^j = \lambda_s^j M_s^j \phi_k^j, \quad j = 1,2,\cdots,n_s; \quad k = 1,2,\cdots,N_s^j \tag{2}$$

ϕ_k^j and λ_k^j are the k^{th} eigenvector and eigenvalue of the j^{th} substructure, respectively. Further, n_s and N_s^j represent the number of substructures and DOFs of the j^{th} substructure. In the CB method, the following transformation matrix is created when the calculation is performed in consideration of the main mode in Eq. (2).

$$\hat{T} = \begin{pmatrix} \phi_d & -K_s^{-1}K_c \\ 0 & I \end{pmatrix}, \quad \hat{T}\hat{u} = \begin{pmatrix} u_s \\ u_b \end{pmatrix}, \quad \hat{u} = \begin{pmatrix} q_d \\ u_b \end{pmatrix}, \quad \psi = -K_s^{-1}K_c \tag{3}$$

$\hat{T}$ represents a transformation matrix, while ϕ_d and ψ are the eigenvalue vector and constraint matrix, respectively. In addition, I and q_d denote the identity matrix and modal coordinate system vector, respectively. Eq. (4) is a reduced equation of motion, derived by utilizing Eq. (3) in Eq. (1).

$$\hat{M}\ddot{\hat{u}} + \hat{K}\hat{u} = \hat{f}, \quad \hat{M} = \hat{T}^T \bar{M} \hat{T}, \quad \hat{K} = \hat{T}^T \bar{K} \hat{T}, \quad \hat{f} = \hat{T} f \tag{4}$$

In general, the DOFs of the reduced-order model were approximately 5 % of the total DOFs (Oh *et al*. 2020). The CB method was used for the finite-element model of the piping, which performed model updating in this study. The reduced-order model used 2 modes and 60 DOFs, corresponding to 10 nodes, as the boundary interface. The 10 nodes are indicated by the red dots in Fig. 7. A reduced-order model with 62 DOFs, which is approximately 1% of the finite-element model with a total of 7428 DOFs, was developed.

2.4 Equation for estimating the responses and load of the digital twin system

The responses of the digital twin system were estimated by applying a direct integration method, namely, the Newmark − β time integration method. Fig. 8 depicts the Newmark − β method process (Newmark 1959).

The Newmark − β method estimates the displacement, velocity, and acceleration of a structure by setting the load as an input value. Using this method, the digital twin system estimated the real-time displacement, velocity, and acceleration of all nodes of the structure using only the measured acceleration data. Information regarding the load is required to obtain a response for all nodes using the Newmark − β method. The seismic load was estimated using the data obtained by attaching an acceleration sensor to the shaking table and the mass matrix of the model. Subsequently, an arbitrary load applied to the measured point on the structure was estimated. This is expressed using Eq. (5) based on the equations of motion.

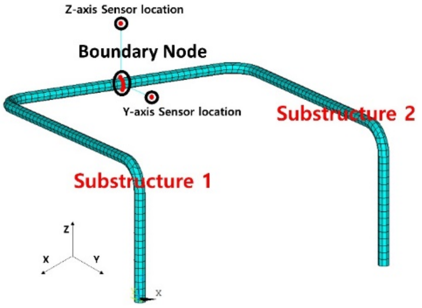


Fig. 7 Nodes used in the reduced-order model of the pipe system

$$\begin{pmatrix} M^m & M^c \\ (M^c)^T & M^{um} \end{pmatrix}\begin{pmatrix} \ddot{u}^m \\ \ddot{u}^{um} \end{pmatrix} + \begin{pmatrix} C^m & C^c \\ (C^c)^T & C^{um} \end{pmatrix}\begin{pmatrix} \dot{u}^m \\ \dot{u}^{um} \end{pmatrix} + \begin{pmatrix} K^m & K^c \\ (K^c)^T & K^{um} \end{pmatrix}\begin{pmatrix} u^m \\ u^{um} \end{pmatrix} = \begin{pmatrix} f_g^m \\ f_g^{um} \end{pmatrix} + \begin{pmatrix} f_s^m \\ 0 \end{pmatrix} \tag{5}$$

The superscripts m, c, and um represent measured, coupling, and unmeasured, respectively. f_s^m is an arbitrary load input at the measurement point of the structure while f_g^m and f_g^{um} denote the seismic loads. Eq. (6) is obtained as an equation of motion for unmeasured points by solving Eq. (5).

$$f_g^{um} = (M^{um}\ddot{u}^{um} + C^{um}\dot{u}^{um} + K^{um}u^{um}) + ((M^c)^T\ddot{u}^m + (C^c)^T\dot{u}^m + (K^c)^T u^m) \tag{6}$$

The responses to the unmeasured points were obtained using Eq. (6). Subsequently, f_s^m , which is an arbitrary load applied to the measurement points, was derived as follows

$$f_s^m = (M^m\ddot{u}^m + C^m\dot{u}^m + K^m u^m) + (M^c\ddot{u}^{um} + C^c\dot{u}^{um} + K^c u^{um}) - f_g \tag{7}$$

$$f^m = f_s^m + f_g^m \tag{8}$$

Eq. (8) represents the total load applied to the structure. Therefore, the responses at the position where the sensor is not attached and at an arbitrary load from some of the

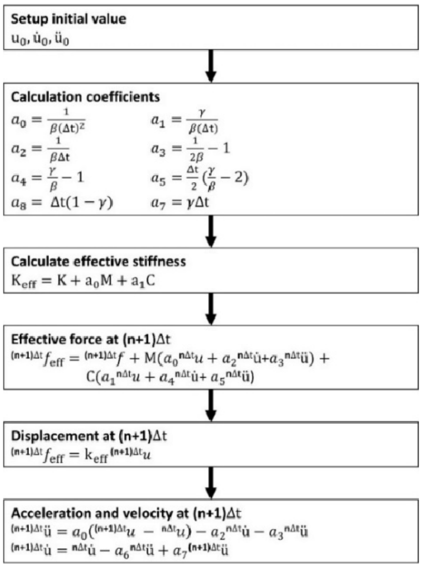


Fig. 8 Procedure of the Newmark − β time integration

acceleration responses may be estimated using the above equation.

3. Application and verification of the constructed digital twin piping system

In this section, the digital twin system built on the target pipe is applied. The load acting on the pipe system was installed on the shaking table to simulate the seismic load. Simultaneously, an arbitrary load was applied to the pipe system using an actuator. The DOFs of the reduced-order model used in the digital twin system of the pipe system were expressed as 62 DOFs, and approximately 1% of the DOFs were utilized compared to the initial finite-element model. The digital twin system operated for 25 s and successfully estimated the responses of the unmeasured points and arbitrary load on the pipe system in real-time.

The measured seismic acceleration data is input into the digital twin system. The seismic acceleration history curve input to the shaking table is shown in Fig. 9. The digital twin system also successfully estimated the arbitrary load acting on the pipe system, which is shown in Fig. 10. Afterward, a comparison was conducted with the response obtained by the digital twin system and the response obtained from the sensor. As shown in Fig. 11, the acceleration responses measured in the pipe system and that estimated by the digital twin system coincide well. Table 2 shows the RMSE (Root Mean Squared Error) values of the estimated responses from the digital twin system and measured responses from the sensors.

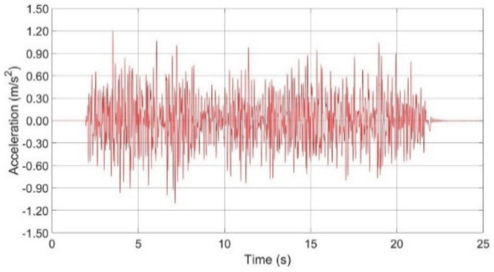


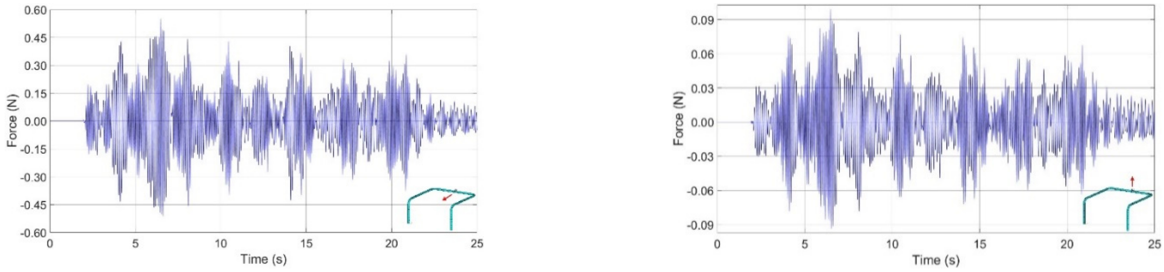
Fig. 9 Input acceleration in the shaking table

The constructed digital twin system can estimate the responses at locations where the sensor is not attached. As an example, Fig. 12 shows the responses near the boundary condition of the pipe system and at a random location in the pipe system. The digital twin system successfully estimated the response of the unmeasured points on the pipe system and it can estimate all 7,428 DOFs responses based on the finite-element model using the transformation matrix used in the reduced-order model.

The constructed digital twin system improved the numerical model calculation ability by about 450 times. Therefore, the digital twin system was capable of real time estimation through high speed calculation. The responses estimated from the digital twin system and finite-element model were compared to verify the constructed digital twin system. The measured acceleration history curve and estimated load of the digital twin system were used for

Table 2 RMSE value of the digital twin response and experiment data

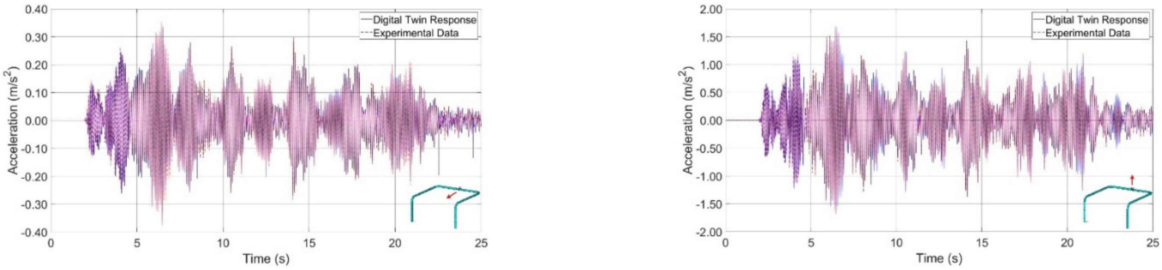
	RMSE value
Y-axis response	0.0103
Z-axis response	0.0266



(a) Y-axis response

(b) Z-axis response

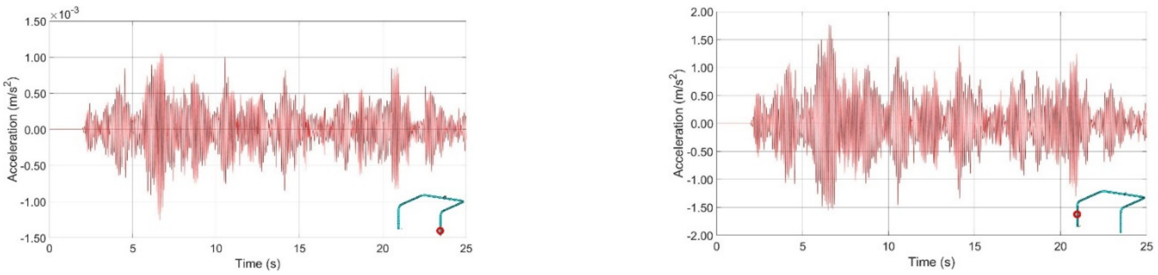
Fig. 10 Estimation of an arbitrary load using the digital twin



(a) Y-axis response

(b) Z-axis response

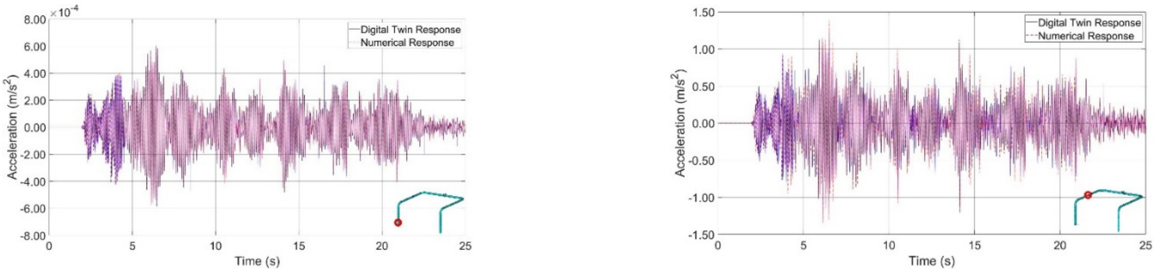
Fig. 11 Comparison of the estimated acceleration



(a) Around the boundary condition of the pipe

(b) Random location in the pipe

Fig. 12 Estimate response at unmeasured points on the pipe



(a) Lower part response of the pipe

(b) Side part response of the pipe

Fig. 13 Comparison of responses of the digital twin and finite-element models

Table 3 RMSE value of the digital twin and numerical response

	RMSE value
Lower part response of the pipe	0.01981
Side part response of the pipe	0.01890

the seismic and erratic loads, which were input values to the finite-element model. The comparison with the response of the lower and side parts, which is an unmeasured point of the pipe system confirmed the similar values of the two responses, as shown in Fig. 13. The RMSE values for this are shown in Table 3. Hence, it can be seen that the proposed digital twin system of the pipe system consistently estimates the response and arbitrary load of measured/ unmeasured points in real time.

4. Conclusions

The PHM of a structure necessitates the measurement of its response using several sensors. However, installing sensors at all points in a structure is uneconomical, and it is difficult to directly measure physical quantities for health monitoring. Therefore, digital twin systems are being utilized for health monitoring in industries. Accordingly, the proposed digital twin system estimates the responses of unmeasured points and an arbitrary load on a structure using the response measured with a minimum sensor. The experimental results showed that the constructed digital twin system efficiently estimated the responses of all piping points and load acting on the pipe system in a short time. The estimated response and arbitrary load were validated by comparing them with the results of the finite-element model with 7,428 DOFs, which demonstrated the high accuracy of the proposed system. This system is capable of estimating the stress, deformation, and strain of the structure in real time based on the estimated response and load. Hence, it is possible to predict the lifespan of the pipe to prevent failure and deterioration. The digital twin system proposed through continuous development is expected to be used in various fields such as ports, shipbuilding, power generation, and manufacturing by identifying the real-time status and safety related to structures and equipment.

Acknowledgments

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