Structural Engineering and Mechanics, *Vol. 57, No. 5 (2016) 921-936*
DOI: http://dx.doi.org/10.12989/sem.2016.57.5.921

Transient response analysis by model order reduction of a Mokpo-Jeju submerged floating tunnel under seismic excitations

Jeong Sam Han[2], Boreum Won[1], Woo-Sun Park[1] and Jin Hwan Ko*[1]

[1]*Coastal Engineering Research Division, Korea Institute of Ocean Science and Technology, Korea*
[2]*Department of Mechanical Design Engineering, Andong National University, Korea*

(Received July 29, 2015, Revised January 8, 2016, Accepted January 27, 2016)

Abstract. In this study, a model order reduction technique is applied to solve the transient responses of submerged floating tunnel (SFT) from Mokpo to Jeju under seismic excitations. Because the SFT is a very long structure as well as a transient response analysis requires large amount of computational resources, the model order reduction is mandatory in the design stage of the SFT. Thus, we apply a model order reduction based on Krylov subspace to the simplified finite element model of the SFT. The responses of the reduced order model are compared with those of the full order model and also are verified by referring a previous work. In conclusion, the computational resources are dramatically reduced with an acceptable accuracy by using the model order reduction, which eventually is useful for designing the full-scale model of SFTs.

Keywords: computational mechanics; dynamic analysis; earthquake/seismic ananysis; finite element method (FEM); numerical methods; offshore/coastal structures; simulation; structural design

1. Introduction

A submerged floating tunnel (SFT) as a floating structure in the sea water takes advantageous over conventional crossings such as a bridge specifically in a short strait of deep depth; thus, many researches related to SFT have been recently conducted. Norway, Italy, and Japan have initiative due to early starting with application to such a short strait in its territory, now a day, China catch up the leading countries. In Japan, research group of SFD was established in 1991, feasible studies for its implementation have been tackled by numerical and experimental approaches. Moreover, this group first conducts a feasible design for Funka bay in Japan (Kanie 2010).

Korea is categorized as one of following group and Korea Institute of Ocean Science and Technology (KIOST) is an active group for this research. As a first project, “core technology of submerged floating tunnel” was started from 2010 and now is in final year, 2015. A feasible design from Mokpo to Jeju is conducting in this project. In the all designed routines from Mokpo to Jeju, 30-40 km short strait in around 100 m depth is existed and SFT is turn to be most economic crossing for this interval.

*Corresponding author, Ph.D., E-mail: jhko@kiost.ac.kr

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Road and rail can be built in SFT, the plan includes only rail in it due to financial issue. SFT as an extreme long structure is floating in the sea water and vulnerable under strong wave, ambient flow, and seismic excitation. Thus, the displacements and accelerations due to them should be estimated in the stage of design. Fortunately, acceptance range about them for the rail construction is large than that of road (RS-SFT 2010).

Among the external loadings, the seismic excitation is serious for the safety of the structure. The response spectrum method is one of main techniques in analyzing the response under the excitation, but in order to obtain the maximum displacements and accelerations under arbitrary excitation, the transient response analysis is mandatory. The transient response analysis requires huge amounts of computational resources. Thus, it is high burden in terms of computation to conduct the transient response analysis for the extreme long structure up to 40 km. So, we adopt two ways for the reduction of the burden; simplification in modeling and model order reduction (MOR), which is famous method for the reduction of the computation.

In the field of structural dynamic analysis, several methods of model order reduction such as the mode superposition method (Craig 1981), the modal acceleration method (Cornwell *et al.* 1983), the load dependent Ritz vector (LDRV) method (Wilson *et al.* 11982) have been suggested to obtain transient responses in an efficient way. The mode superposition method is a classical method and exploits the undamped eigenvectors as a projection subspace because it has explicit physical meaning. It simultaneously diagonalizes both the mass and stiffness matrices of the system and preserves the system's undamped natural frequencies (Craig 1981). Using the method for large-scale systems may be cost-prohibitive in terms of computational cost the necessary eigenvectors with satisfactory accuracy. This shortcoming can be overcome to some extent through the use of modal truncation schemes that only retain the reduced number of eigenvectors. However, the truncated errors of transient responses from a modal truncation scheme can sometimes be very significant. Therefore, its improved variants, such as the modal acceleration method, have been proposed to compensate for the effect of neglected high-frequency modes (Cornwell *et al.* 1983). In the load dependent Ritz vector method, a sequence of mass and stiffness orthogonal Ritz vectors is adopted to reduce the size of the system. The vectors can be generated at a fraction of the cost required to calculate eigenvectors in the mode superposition method since the load dependent Ritz vectors are generated from the externally applied load and are orthonormalized in terms of the mass matrix using the Gram-Schmidt orthogonalization procedure. Kline (1986) reported that when some eigenvectors are already available, adding a few load dependent Ritz vectors to the basis is an easy way to increase the accuracy of transient analysis results. The generation of few load dependent Ritz vectors is identical to the Lanczos algorithm (Kim 1988) applied with full reorthogonalization if the same initial vector is used but the Lanczos algorithm originates from mathematics, whereas the load dependent Ritz method arises from engineering.

As relatively recent interests in calculation of frequency responses using model order reduction, substructuring-based model reductions have been developed to improve efficiency in approximate frequency response analysis of large-scale systems. Substructuring reduction for the iteratively improved reduced system (Choi *et al.* 2008), algebraic substructuring (Gao *et al.* 2008), and combination of a subdomain method and a reduction method (Kim *et al.* 2011) are included in this category. Ko *et al*. (2009) reported a variant of algebraic substructuring using the mode superposition method enhanced by the so-called frequency sweep algorithm to obtain frequency responses near an extremely high-frequency range of interest. For dynamic problems in time domain, Choi *et al*. (2008) developed substructuring based model reductions to improve efficiency in transient analysis of large-scale systems.

In this paper, an efficient model reduction method that utilizes the Krylov subspace-based model order reduction (Han 2013, Freund 2000, Bai 2002) is adopted in order to calculate the approximation of transient seismic responses for submerged floating tunnel (SFT) from Mokpo to Jeju under seismic excitations. The main idea herein is that the equations of motion are reduced using a projection matrix generated from Krylov basis vectors instead of using the full-size system. Because the seismic loads are multi-dimensional in this case, the Krylov basis vectors are generated by the block-Arnoldi algorithm (Rudnyi 2006) which consists of a series of static solutions. Afterward direct transient seismic analyses for the reduced system are performed using the Newmark's time integration method (Bathe 1996). Thus, we apply a model order reduction based on Krylov subspace to the simplified finite element model of the SFT. The transient responses from the reduced order model are compared with those from the full order model (FOM) in terms of accuracy and computational cost.

2. Methods

2.1 Problem definition and the implementation of ocean conditions

At present, no case of SFT construction is reported over the world. In Korea, plans for SFT construction have been established in crossings between Japan and Korea as well as between Mokpo and Jeju, however the real construction is not started due to financial issues. These days, the airway from Jeju and Kimpo is recorded as the busiest airway in the world; thus, new airport construction is considered. The crossing from Mokpo and Jeju becomes another solution, so the feasible design is conducted in certain range around 30-40 km among the full crossing. SFT is known as an economic crossing in short strait of relatively deep depth, and is composed of tubes, tension legs, joints and ventilation towers.

Due to that SFT is deployed in the sea water, added mass and hydrodynamic damping should be considered in dynamic analysis of it. First, the added mass in water can be calculated as follows (Newmark 1971)

$$\begin{aligned} & m_{added} = \rho_w \pi r^2 \sin\theta \\ & \rho_w : \text{density} \\ & r \ \ : \text{radius} \\ & \theta \ \ : \text{angle between flow direction and longitudinal direction of structure} \end{aligned} \tag{1}$$

Added mass calculated from Eq. (1) is implemented in modeling by modifying the material property of a finite element model. Next, the hydrodynamic damping is calculated by following equation with four components

$$\begin{aligned} & D_{add,offsh} = D_{radiation} + D_{vis,hydro} + D_{steel} + D_{soil} \\ & \text{with } D_{radiation}\text{: damping from wave creation due to structure vibration} \\ & \qquad D_{vis,hydro}\text{: viscous damping due to hydrodynamic drag} \\ & \qquad D_{steel} \quad \text{: material damping of steel} \\ & \qquad D_{soil} \quad \text{: soil damping due to inner soil friction} \end{aligned} \tag{2}$$

According to offshore technology conference report (Cook *et al*. 1982), the values of the components in Eq. (2) can be estimated by

$$\begin{aligned} &D_{radtion} = 0.22\%,\ D_{vis,hydro} = 0.15\% \\ &0.2\% \le D_{steel} \le 0.3\%,\ D_{soil} = 0.53\% \end{aligned} \tag{3}$$

A famous ocean engineering company, Garrad Hassan also reported the following suggestion range for pile supporting structures

$$D_{add,offsh} = 0.8 - 1.2\%,\ \text{Best estimate}\ \ 0.9\% \tag{4}$$

The design SFT here is supported by a tension leg instead of a pile; D_{soil} of the tension leg is a little smaller than that of the pile, but the damping of concrete is a little larger than that of steel; thus, 1% damping is used in our structure.

2.2 Simplification in modeling

2.2.1 Simplification of tube by beam element

First, the tube with an arbitrary section should be modeled by shell or solid elements for high accuracy, which yields large computation. Thus, a simplification technique using beam elements is necessary, and the simplified model should be similar in terms of its accuracy as compared to corresponding shell or solid element models.

Fig. 1 shows simplified and corresponding shell element models of 300m single tube. ANSYS BEAM188 is used as the beam element, and actual section is implemented by using MESH function. The shell model is composed of 136,824 elements and 134,049 nodes. The beam element is composed of 600 elements and 1,201 nodes; thus the number of degree of freedom (DOF) is reduced less than 1/100.

End sections are fixed. 30 GPa young’s modulus for concrete, 2497 kg/m^3 density (ρ), 1/6 Poisson’s ratio are used. For comparison, static and eigenvalue analyses are conducted, and 1G acceleration is used for the static analysis.

Fig. 2 shows displacement contours of the static analysis. The maximum displacement of the shell model is 0.568 and that of the beam model is 0.567; thus they almost same less than 1% error.

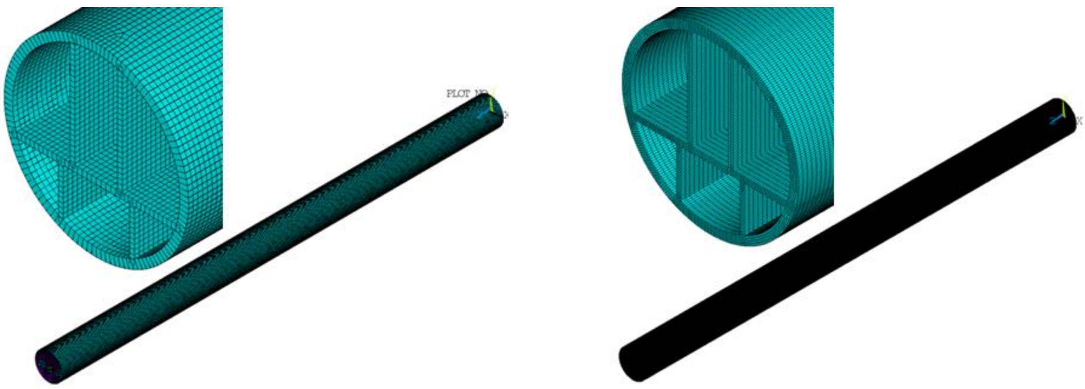


Fig. 1 shell model and simplified beam model

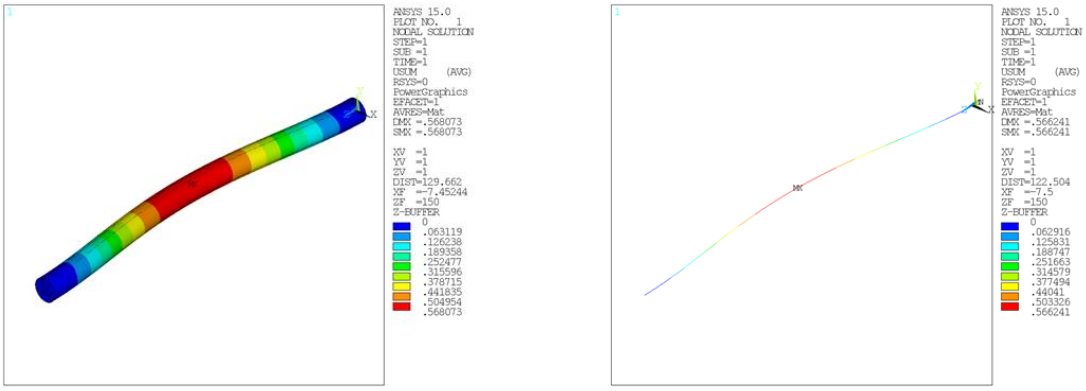


Fig. 2 Displacements of shell and beam models

Table 1 Eigenvalues of shell and beam models

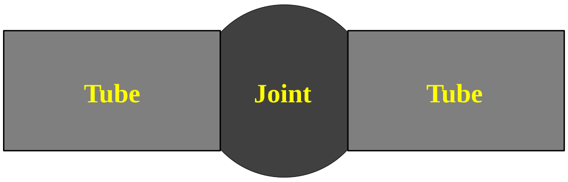
Shell		Beam	
Mode	Frequency (Hz)	Mode	Frequency (Hz)
1	0.75454	1	0.75454
2	0.77050	2	0.77050
3	1.9699	3	1.9699
4	2.0232	4	2.0232
5	3.5084	5	3.5084
6	3.6194	6	3.6194
7	3.7455	7	3.7455
8	5.4335	8	5.4335
9	5.5382	9	5.5382
10	5.6678	10	5.6678

Next, Table 1 listed 10 eigenvalues from the eigen-analysis and both results are almost identical as well. Therefore, the simplified beam model can be substituted for the shell model in following dynamic analysis.

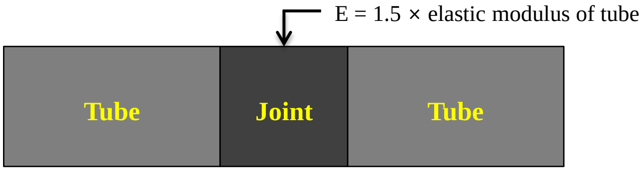
2.2.2 Simplification of other components

Single tubes are connected each other to be full SFT. The joint for the connection is designed for structural safety and stability so that a tight connecting joint is preferred to a soft connecting joint, of which some DOF are not constrained. Thus, the joint is modeled by the tight connecting type in design. That is, this is considered as a tight joint with different materials; thus, nodes in the interface are shared and the material property is increased to 1.5 times in the simplified joint model of which the length is 40 m as shown in Fig. 3.

The material properties of the tension leg are brought from a previous study: tensional strength is 1,600 MPa, yield strength is 1,200 MPa, and Young's modulus is 200,000 MPa (RS-SFT 2010). In this study, crossing type with 4 tensioners is adopted as shown in Fig. 4 due to minimizing the longitudinal displacement of the tube.



[Conceptual drawing of joint]



[Simplified joint]

Fig. 3 Simplification of joint

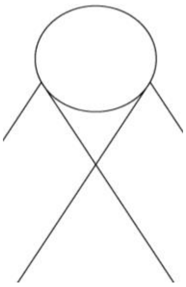


Fig. 4 Tension leg type (30 degree inclination angle)

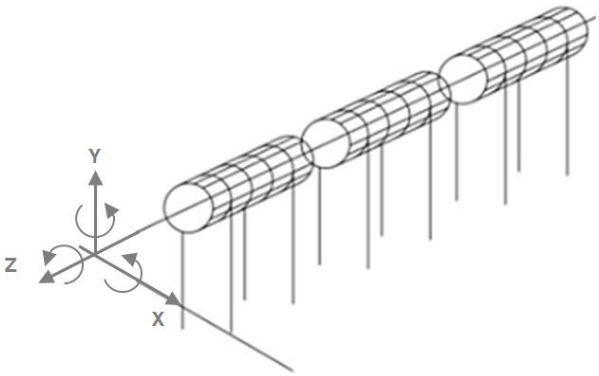


Fig. 5 Coordinates of SFT

Initial tension per each tension leg (Ti) is 6626 tonf, and in final limitation status level 2 (1≤*T*≤*Ty* where *Ty* is yield limitation tension) section area is 1,104 cm^2. The coordinate of the SFT is shown in Fig. 5.

Recovery force along each direction per each tension leg is calculated as follows (RS-SFT 2010). First, the recovery force of transverse direction (x) of 4 tension legs is defined by

$$K_x = \frac{4EA\sin^2\theta}{L_s} \tag{5}$$

Next, the recovery force of vertical direction (y) is calculated by

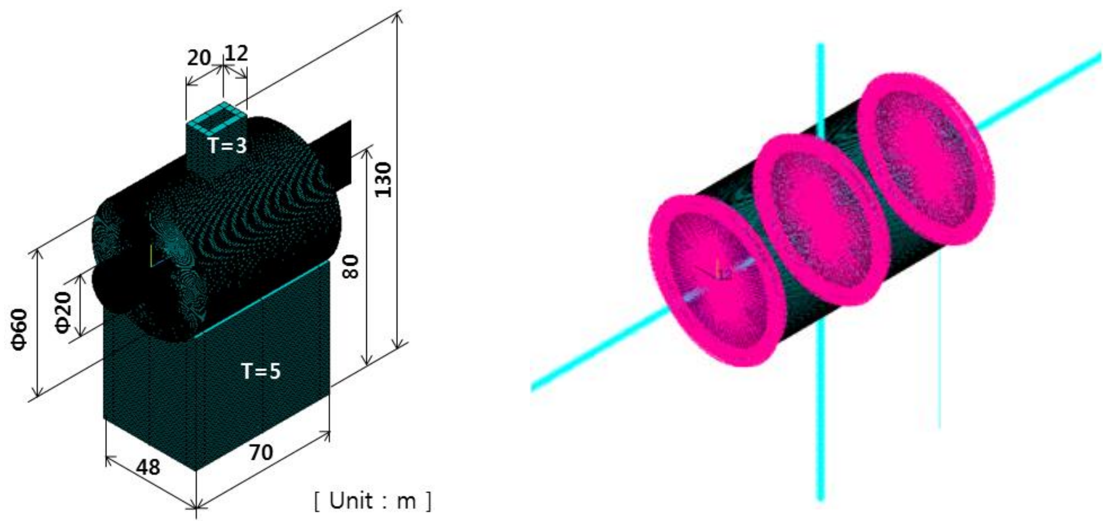
$$K_y = \frac{4EA\cos^2\theta}{L_s} \tag{6}$$

Last, the recovery force of longitudinal direction (z) is defined by

$$K_z = 2\frac{P_v}{L_v} \tag{7}$$

where, K_i is i-directional recovery force (tonf/m^2), P_v is the initial tension of the tension leg, E is Young's modulus of the tension leg (tonf/m^2), A is the sectional area of the tension leg (m^2), L_v is the length of the tension leg along the vertical direction (m), L_s is the length of the tension leg (m), and θ is the inclination angle of the tension leg (30°). The recovery forces through Eqs. (5)-(7) are implemented in the modeling into spring elements.

Other structure attached to the tube is the ventilation tower, which constrains the large displacement due to very long structure and has ventilating function as well as evacuation function at emergency situation. The ventilation tower is slightly simplified and modeled with shell and beam elements as shown in Fig. 6(a). The bottoms of the ventilation towers are connected to a large mass where the seismic excitation is applied. Considering path between the tube and the tower, all DOF are constrained at the middle section by RBE elements and all DOF except longitudinal translation and rotation are constrained at the both end sections by RBE elements (see Fig. 6(b)).



(a) FE model with dimension of a ventilation tower (b) Connection between a tower and tubes

Fig. 6 Finite element model of a ventilation tower and RBE connection

2.2.3 Seismic excitation load modeling

Seismic excitation is imposed at constraint points; thus, general loading imposition technique is not possible to be applied. Therefore, a special way for the imposition is necessary and a famous one is Large Mass Method (LMM). LM is rigidly connected to excitation points, the displacement is calculated by Mass*Acceleration (*F=ma*), and velocity/acceleration are then obtained by the calculated displacement. Another way is recently developed method, Enforced Motion Method (EMM), in which the acceleration is imposed to excitation points (Senousy 2013). Meanwhile, EMM already includes a model order reduction technique, so additional model order reduction is hard to be applied. In this study, LMM is used due to the reason.

Generally, seismic excitation load is different at each supporting positions, but it is not easy to obtain the load at each point from real measured data due to high cost as well as seismic propagating algorithm due to few available code. So, we only adopt measured data at a single point from previous work.

2.3 Krylov subspace based model order reduction

In structural dynamic problems, the general dynamic equation is given by a second-order system of ordinary differential equations (ODEs)

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{x}}(\mathrm{t}) + \mathbf{C}\dot{\mathbf{x}}(\mathrm{t}) + \mathbf{K}\mathbf{x}(\mathrm{t}) = \mathbf{F}(\mathrm{t}) \\ &\mathbf{y}(\mathrm{t}) = \mathbf{L}\mathbf{x}(\mathrm{t}) \end{aligned}, \tag{8}$$

where t is the time variable, $\mathbf{x}(\mathrm{t})\in\Re^{\mathrm{N}}$ is a vector of state variables, and $\boldsymbol{y}(t)\in\Re^{\mathrm{p}}$ is the output observation vector. A set of initial conditions and is assumed on $\mathbf{x}(t)$. The matrices $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}\in\Re^{\mathrm{N\times N}}$ are the structural mass, damping, and stiffness matrices of the system, respectively. $\mathbf{F}\in\Re^{\mathrm{N}}$ and $\mathbf{L}\in\Re^{\mathrm{p\times N}}$ are a force vector from seismic excitations and an output measurement matrix, respectively, for the observation at certain locations. N is the dimension of the state variable vector $\mathbf{x}(t)$ and p is the number of output degrees of freedom of the system. In many engineering cases, p is considerably smaller than N.

The basic concept of model order reduction (MOR) based on the Krylov subspace is to find a low-dimensional subspace $\mathbf{V}^{\mathrm{N\times n}}$ of

$$\mathbf{x}(\mathrm{t}) \cong \mathbf{V}\mathbf{z}(\mathrm{t}) \quad \text{where} \quad \mathbf{z}(\mathrm{t}) \in \Re^{\mathrm{n}}, \ \mathrm{n} << \mathrm{N} \tag{9}$$

such that the response of the original high-dimensional state vector $\mathbf{x}(t)$ in Eq. (8) can be well approximated by the projection matrix $\mathbf{V}$ in relation to a considerably reduced vector $\mathbf{z}(t)$ of order n. The velocity and acceleration are expressed from this relation as

$$\dot{\mathbf{x}}(\mathrm{t}) = \mathbf{V}\dot{\mathbf{z}}(\mathrm{t}), \quad \ddot{\mathbf{x}}(\mathrm{t}) = \mathbf{V}\ddot{\mathbf{z}}(\mathrm{t}) \tag{10}$$

Provided that the Krylov subspace $\mathbf{V}$ is found, the original Eq. (8) is projected onto $\mathbf{V}$ and multiplication of $\mathbf{V}^{\mathrm{T}}$ yields the reduced system as follows

$$\begin{aligned} &\underbrace{\mathbf{V}^{\mathrm{T}}\mathbf{M}\mathbf{V}}_{\mathbf{M}_{\mathrm{r}}}\ddot{\mathbf{z}}(\mathrm{t}) + \underbrace{\mathbf{V}^{\mathrm{T}}\mathbf{C}\mathbf{V}}_{\mathbf{C}_{\mathrm{r}}}\dot{\mathbf{z}}(\mathrm{t}) + \underbrace{\mathbf{V}^{\mathrm{T}}\mathbf{K}\mathbf{V}}_{\mathbf{K}_{\mathrm{r}}}\mathbf{z}(\mathrm{t}) = \underbrace{\mathbf{V}^{\mathrm{T}}\mathbf{F}}_{\mathbf{F}_{\mathrm{r}}}(\mathrm{t}) \\ &\mathbf{y}(\mathrm{t}) = \underbrace{\mathbf{L}\mathbf{V}}_{\mathbf{L}_{\mathrm{r}}}\mathbf{z}(\mathrm{t}) \end{aligned} \tag{11}$$

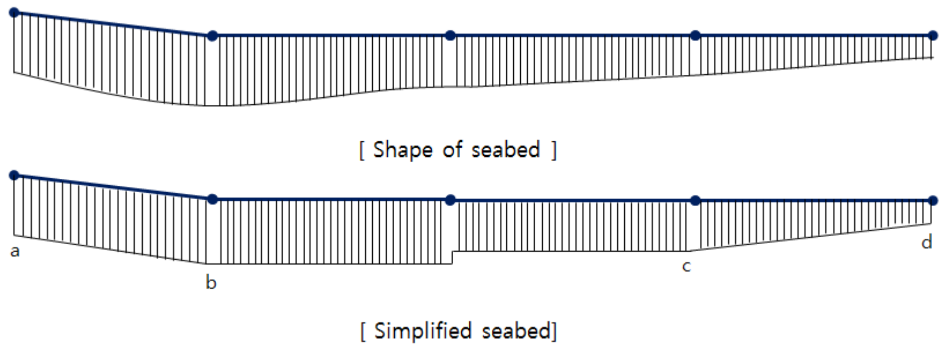


Fig. 7 Simplification of seabed

with the following initial conditions

$$\mathbf{z}(0) = \mathbf{V}^T \mathbf{x}(0), \quad \dot{\mathbf{z}}(0) = \mathbf{V}^T \dot{\mathbf{x}}(0) \tag{12}$$

The system matrices in the reduced system are denoted as $\mathbf{M}_r = \mathbf{V}^T\mathbf{M}\mathbf{V}$, $\mathbf{C}_r = \mathbf{V}^T\mathbf{C}\mathbf{V}$, $\mathbf{K}_r = \mathbf{V}^T\mathbf{K}\mathbf{V}$, $\mathbf{F}_r = \mathbf{V}^T\mathbf{F}$, and $\mathbf{L}_r = \mathbf{L}\mathbf{V}$. The most efficient way to compute a reasonably accurate basis for the Krylov subspace is implicit moment matching through the Arnoldi process (Freund 2000). When the loading is multi-dimensional as the seismic excitations, the block-Arnoldi algorithm (Rudnyi 2006) is more appropriate. In terms of the moment-matching method for a second-order dynamical system, it is shown that the reduced system in Eq. (11) matches the first n moments of the full-order system in Eq. (8) if the projection matrix $\mathbf{V}_n$ is chosen from the nth Krylov subspace K_n given as

$$\text{colspan}\{\mathbf{V}_n\} = \mathcal{K}_n(\mathbf{K}^{-1}\mathbf{M}, \mathbf{K}^{-1}\mathbf{F}) = \text{span}\{\mathbf{K}^{-1}\mathbf{F}, (\mathbf{K}^{-1}\mathbf{M})\mathbf{K}^{-1}\mathbf{F}, \cdots, (\mathbf{K}^{-1}\mathbf{M})^{n-1}\mathbf{K}^{-1}\mathbf{F}\} \tag{13}$$

When multiple inputs such as seismic excitations are considered, the Krylov subspace is generated by

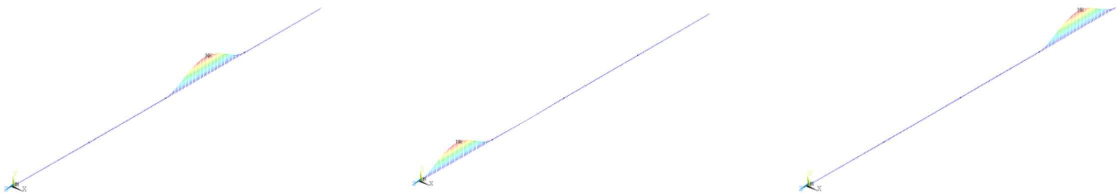
$$\text{colspan}\{\mathbf{V}_n\} = \mathcal{K}_n(\mathbf{K}^{-1}\mathbf{M}; \mathbf{K}^{-1}\mathbf{F}_{ax}, \mathbf{K}^{-1}\mathbf{F}_{ay}, \mathbf{K}^{-1}\mathbf{F}_{az}) \tag{14}$$

Numerically, the Arnoldi process generates the projection matrix $\mathbf{V}_n$ to be orthonormal. Thus, $\mathbf{V}^T\mathbf{V} = \mathbf{I}_n$. Note that the reduction of the dimension of the systems to $n<<N$ is achieved in Eq. (11) while the output vector $\mathbf{y}(t)$ retains the same size as that in Eq. (8), with the result that transient dynamics responses can be very efficiently calculated from Eq. (11). It is also noted that the generated vectors from both Krylov subspace MOR and the LDRV method are very similar but the former originates from applied mathematics, whereas the latter arises from engineering.

2.4 Results and discussions

2.4.1 Full modeling and results from eigen-analysis

Aforementioned, SFT is composed of tubes, joints between tubes, tension legs, and ventilation towers and its length is up to 40 Km. In order to conduct a transient response analysis of a very long and complex structure, the simplification techniques described in the method section are applied as well as the seabed of SFT is also simplified as shown in Fig. 7. Namely, after separating 4 sub-ranges, linearization for each sub-range is applied and the depths of the separating points are

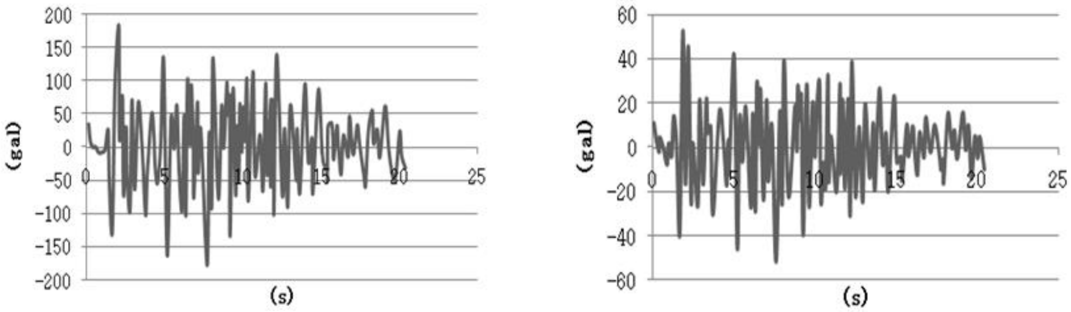


(a) Mode 1 (0.46×10^{-3}Hz) (b) Mode 2 (0.48×10^{-3}Hz) (c) Mode 3 (0.49×10^{-3} Hz)

Fig. 8 Modal frequency and mode shape

Table 2 Excitation condition (gal=cm/s^2)

Limitation status	Final limitation status
	Level 2
Duration	950 years
Maximum horizontal acceleration	189 gal
Maximum vertical acceleration	53 gal



(a) Horizontal (X-) direction (b) Vertical (Y-) direction

Fig. 9 Time history of horizontal and vertical seismic excitations

a=25 m, *b*=105 m, *c*=95 m, and *d*=30 m. The ventilation tower is located at the separating point (·), and the end points of total SFT are constrained in all DOF. The tension leg is modeled by the spring element in ANSYS, COMBIN14 of which the number is 795. The length of the single tube is 300 m and SFT is then composed of 133 tubes. The number of total elements is127,238, the number of nodes is 207,083, and the number of total DOFs is 1,122,978 even though the prescribed simplified techniques are applied.

For the validation of the dynamic characteristic of the full model, eigen-analysis is conducted with Block Lanczos method option. As shown in Fig. 8, the main modes are bending near both ends and a ventilation tower. The eigenvalue is quite small in 10^{-3} level due to that SFT is a very long flexible structure.

2.4.2 Results of dynamic responses

The object of the seismic response analysis is to obtain the maximum displacement and acceleration under seismic excitation for judging the structural safety as compared with the results of the Funka bay in Japan. Excitation condition and excitation loads are from the previous work

Table 3 Criteria of the maximum displacement and acceleration and judgment of results

Direction	Displacement		Acceleration	
	Criterion	Judgment	criterion	Judgment
Horizontal	170 cm	O.K.	100 gal	Remodeling
Vertical	7.7 cm	Remodeling	130 gal	O.K.

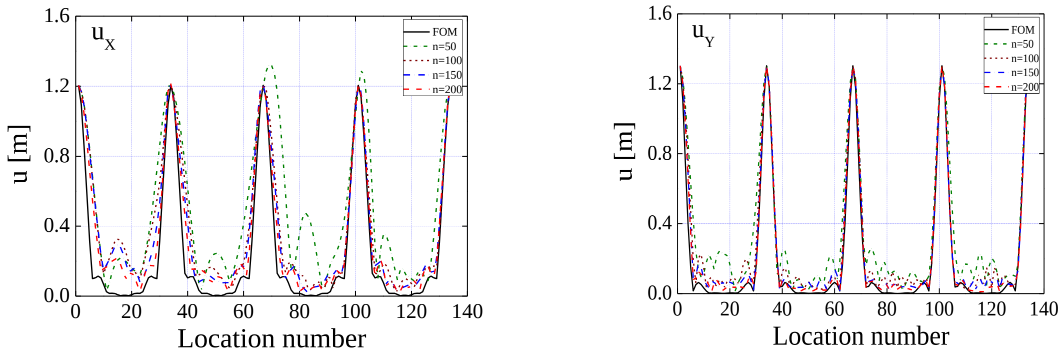


Fig. 10 Comparison of maximum absolute displacement at the 134 location points along the SFT

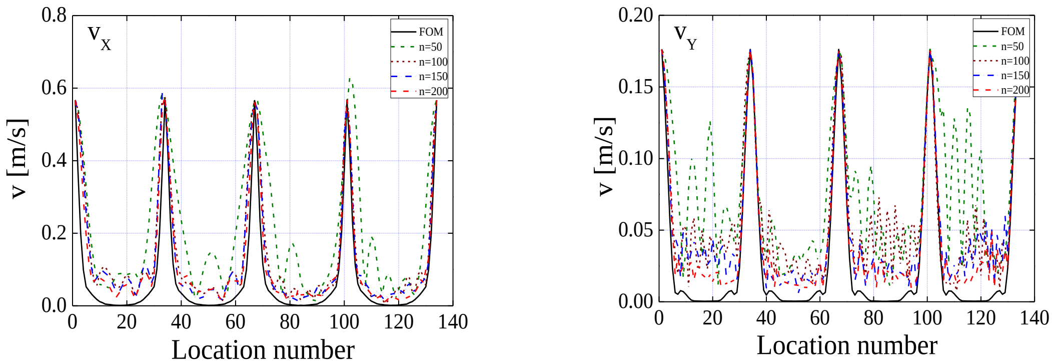


Fig. 11 Comparison of maximum absolute velocity at the 134 location points along the SFT

(RS-SFT 2010). Therefore, direct comparison and the use of the safety criterion presented in the reference are possible.

The seismic accelerations in Fig. 9 are imposed to an artificial large mass which is used for the large mass method (ANSYS 2015). The displacement and acceleration responses are 1.21 m, 1.66 m/s^2, respectively in the horizontal direction and 1.30 m, 0.45 m/s^2, respectively in the vertical direction. Judgment based on the criteria of the previous report (RS-SFT 2010) is listed in Table 3. The judgment is useful to decide whether remodeling to achieve the structural safety is necessary or not.

2.4.3 Comparison and discussion of transient responses

In this section, the numerical accuracy and computational cost of reduced-order models (ROMs) are compared with the full-order model (FOM). The transient seismic responses such as maximum absolute displacement, velocity, and acceleration at the 134 location points along the

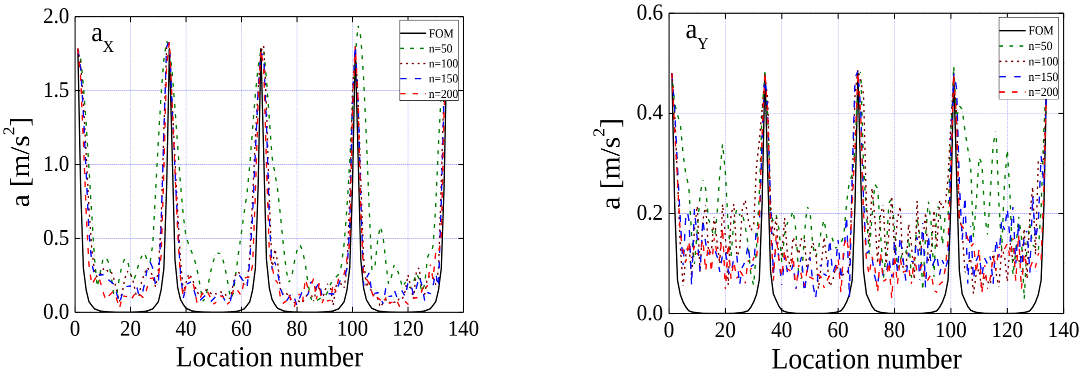


Fig. 12 Comparison of maximum absolute acceleration at the 134 location points along the SFT

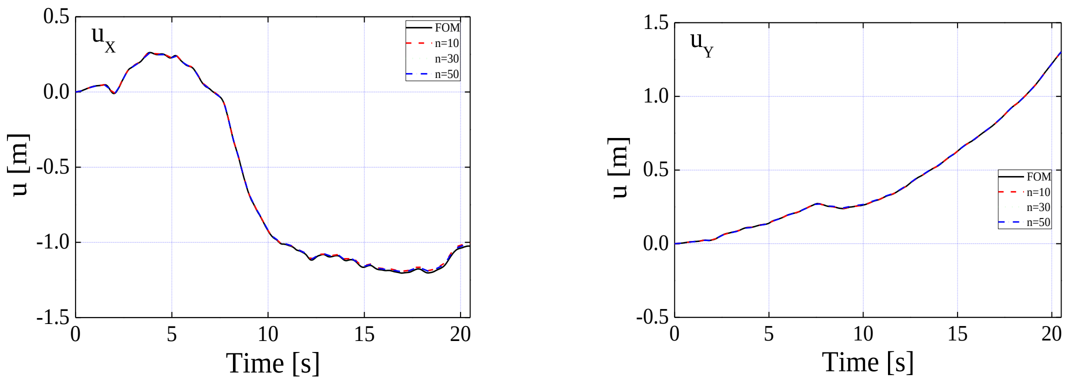


Fig. 13 Comparison of displacement at location number 67

SFT using the FOM are compared with those using ROMs of orders n=50, 100, 150 and 200 as shown in Figs. 10-12. The results even from ROM (n=100) give very accurate approximation of maximum absolute displacement, velocity, and acceleration at the every peaks corresponding to the ventilation towers of SFT. Those maximum absolute responses using higher order ROMs gives a perfect match with that using the FOM. Whereas, the approximate responses between the ventilation towers are less accurate and not able to perfectly trace the relatively small values. By increasing the order of ROMs, however, the discrepancies can be reduced to an acceptable level in the engineering perspective.

The time-domain responses using the FOM and ROMs were also compared at two location points along the SFT. The one (location number 67) corresponds to the ventilation tower and the other (location number 70) is located at a point on the tube next to the ventilation tower. In the case of the former, all the transient responses such as displacement and acceleration are indiscernible in the whole time range even from ROM of order 10 as shown in Figs. 13-14. For the latter, of which the results are depicted in Figs. 15-16, the transient responses get closer to those from the FOM by increasing the order of reduced model but are less accurate than the former. The reason is that the mass system matrix is numerically ill-conditioned because of the addition of a large mass from the use of the LMM and the generated Krylov vectors lose numerical independency at relatively low order for multiple force inputs. However, the main interesting

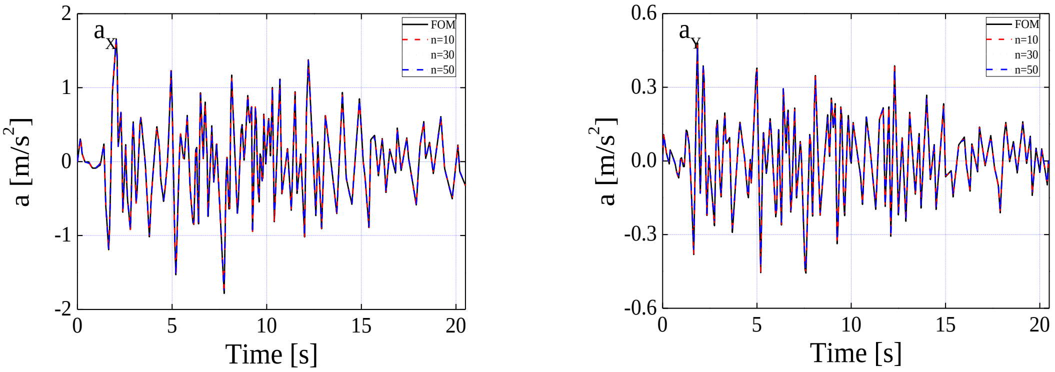


Fig. 14 Comparison of acceleration at location number 67

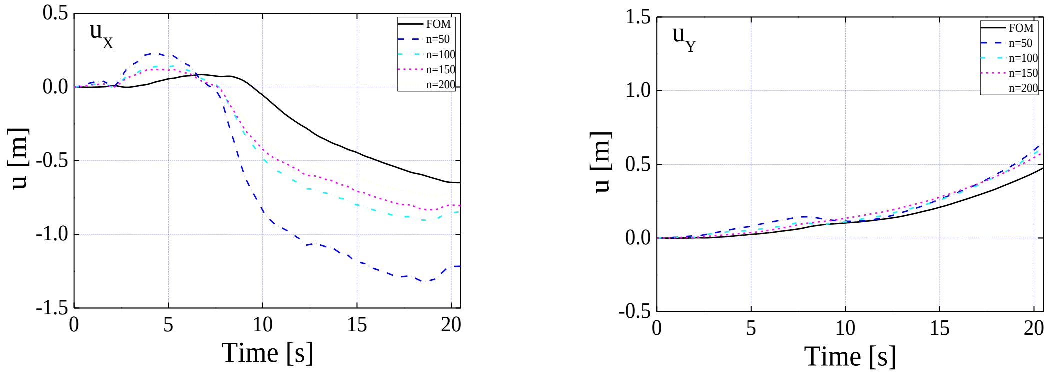


Fig. 15 Comparison of displacement at location number 70

responses, the maximum absolute displacement and acceleration, from the ROMs over order of 100 have the acceptable level of accuracy compared with those from the FOM and may be used to evaluate the satisfaction of the structural safety criteria in design stage. It is worth noting that the displacements in the vertical direction at the location numbers 67 and 70 are still increasing at the end of seismic excitation because the mode shapes of the smallest eigenvalues in Fig. 8 indicate the oscillation in the vertical direction and subsequently the vertical oscillation has a longer period than the horizontal one (see Figs. 13 and 15).

The computational efficiency of the ROMs is compared with the FOM. The calculations were performed using MATLAB R2014a (Mathworks 2015) on an HP workstation with dual Xeon E5-2690 processors and 192 GB RAM. For the FOM of the SFT model, the transient analysis takes about 210,962 sec. including the preparation of the system matrices. On the other hand, the ROMs need computation times for both the generation of Krylov vectors and transient simulation. Thus, the ROMs with n=50, 100, 150 and 200 need highly reduced computational costs for the transient response analysis, that is, roughly 2,879, 5,720, 8,460 and 12,051 sec., respectively. The computation time for the highest order ROM (n=200) are less than 6% of those for the FOM. Therefore, a considerable reduction is achieved in the computational costs for obtaining the transient seismic responses owing to the use of the ROMs. The use of the ROMs becomes more efficient as the size of the FOM and the duration of the seismic excitation increase. It should be

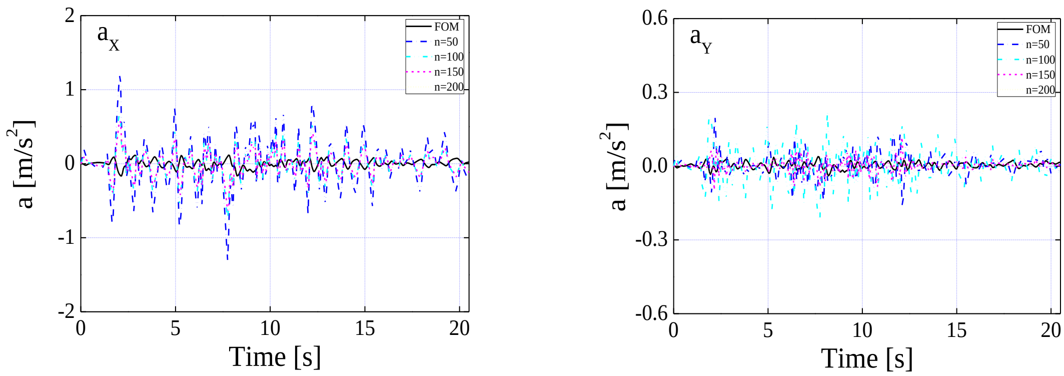


Fig. 16 Comparison of acceleration at location number 70

Table 4 Computation times for obtaining the transient seismic responses

Computation time (s)	FOM	ROM			
		n=50	*n*=100	*n*=150	*n*=200
Total DOF	1,122,186	50	100	150	200
Preparation of the system matrices	304	304	304	304	304
Generation of ROMs	-	2,575	5,414	8,138	11,723
Calculation of transient response	210,658	0.3	2.0	18.4	24.3
Total	210,962	2,879.3	5,720.0	8,460.4	12,051.3

noted that the computation times in Table 4 may vary slightly, depending on the configuration of the computer used for the operation, such as the I/O rates of the hard disk drives and the number of the processes.

3. Conclusions

In this paper, we built up a simplified finite element model for a submerged floating tunnel (SFT) from Mokpo to Jeju and applied a model order reduction technique in order to obtain transient seismic responses in a cost-effective way.

As a simplification approach, beam element modeling is used for the tubes and its model is validated as compared to the corresponding shell model. Tension legs, joints, and ventilation towers in SFT are applied by a simplification technique; thus, one million full model is generated for 40Km SFT. In the transient response analysis, ocean condition is considered by applying added mass and hydrodynamic damping and Large Mass Method is adopted for the imposition of the seismic excitation load.

From the computations, it was shown that transient seismic analysis of large-size FE models were efficiently performed using the Krylov subspace-based MOR with a tremendous time reduction in computation and good accuracy. The responses near at peak positions are highly accurate, the accuracy of other points are pertained with an acceptable level in the engineering perspective. Therefore, this approach can be very useful for the structural optimization due to high computation reduction with acceptable accuracy for the seismic response analysis of the very long structure, SFT.

Acknowledgements

This study is supported by project "Development of core techniques for the practical use of submerged floating tunnels (PE99321)" of Korea Institute of Ocean Science and Technology.

Reference

ANSYS, Inc. (2015), ANSYS mechanical APDL Theory Reference, ANSYS Release 16.1, Canonsburg, USA.

Bai, Z. (2002), "Krylov subspace techniques for reduced-order modeling of large-scale dynamical systems", *Appl. Numer. Math.*, **43**, 9-44.

Bathe, K.J. (1996), *Finite Element Procedures*, Prentice Hall, Upper Saddle River, USA.

Choi, D., Cho, M. and Kim, H. (2008), "Efficient dynamic response analysis using substructuring reduction method for discrete linear system with proportional and nonproportional damping", *KSAS Int. J.*, **9**(1), 85-99.

Choi, D., Kim, H. and Cho, M. (2008), "Improvement of substructuring reduction technique for large eigenproblems using an efficient dynamic condensation method", *J. Mech. Sci. Tech.*, **22**(2), 255-268.

Cook, M.F. and Vandiver, J.K. (1982), "Measured and predicted dynamic response of a single pile platform to random wave excitation", MIT, OTC (Offshore Technology Conference report), 4285.

Cornwell, R.E., Craig, R.R. and Johnson, C.P. (1983), "On the application of the mode acceleration method to structural engineering problems", *Earthq. Eng. Struct. Dyn.*, **11**(5), 679-688.

Craig, R.R. (1981), *Structural dynamics-An introduction to computer methods*, John Wiley, New York, USA.

Freund, R.W. (2000), "Krylov-subspace methods for reduced-order modeling in circuit simulation", *J. Comput. Appl. Math.*, **123**, 395-421.

Gao, W., Li, X.S., Yang, C. and Bai, Z. (2008), "An implementation and evaluation of the AMLS method for sparse eigenvalue problems", *ACM Tran. Math. Softw.*, **34**(4), 20:1-28.

Han, J.S. (2013), "Calculation of design sensitivity for large-size transient dynamic problems using Krylov subspace-based model order reduction", *J. Mech. Sci. Tech*., **27**(9), 2789-2800.

Kanie, S. (2010), "Feasibility studies on various SFT in Japan and their technological evaluation", *Procedia Eng.*, **4**, 13-20

Kim, H.M. and Craig, R.R. (1988), "Structural dynamics analysis using an unsymmetric block Lanczos algorithm", *Int. J. Numer. Meth. Eng.*, **26**(10), 2305-2318.

Kim, H., Cho, M., Kim, H. and Choi, H. G. (2011), "Efficient construction of a reduced system in multi-domain system with free subdomains", *Finite Elem. Anal. Des.*, **47**, 1025-1035.

Kline, K.A. (1986), "Dynamic analysis using a reduced basis of exact modes and Ritz vectors", *AIAA J.*, **24**, 122022-2029.

Ko, J.H., Byun, D. and Han, J.S. (2009), "An efficient numerical solution for frequency response function of micromechanical resonator arrays", *J. Mech. Sci. Tech.*, **23**(10), 2694-2702.

Newmark, N.M. and Rosenblueth, E. (1971), *Fundamentals of Earthquake Engineering*, Prentice-Hall, Engle wood Cliffs, NJ.

Research Society of Submerged Floating Tunnel (RS-SFT) (2010), Underwater submerged tunnel: case study, Research Report.

Rudnyi, E. and Korvink, J. (2006), "Model order reduction for large scale engineering models developed in

ANSYS", Lecture Notes in Computer Science, 3732, 349-356.
Schmidt, B. (2010), Overall Damping for Piled Offshore Support Structures, DWL-Scmi-extern-001.
Senousy, M. (2013), Base Acceleration in Harmonic Analysis, 3 Techniques and 1 ACT Extension.
The MathWorks, Inc. (2015), MATLAB Getting Started Guide, Natick, USA.
Wilson, E.L., Yuan, M.W. and Dickens, J.M. (1982), "Dynamic analysis by direct superposition of Ritz vectors", *Earthq. Eng. Struct. Dyn.*, **10**, 813-821.

CC