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VFIFE METHOD APPLIED FOR OFFSHORE TEMPLATE STRUCTURES UPGRADED WITH DAMPER SYSTEM

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Key words: offshore platform system, temple platform structure, vibration mitigation, visco-elastic material, VFIFE method.

ABSTRACT

In this study, a plane frame element derived from vector form intrinsic finite element (VFIFE) method is adapted and applied to study the dynamic responses of an offshore template platform subject to wave forces. Furthermore, this vector form intrinsic finite element is modified in order to incorporate a visco-elastic material, which has excellent energy-absorption ability, to a damping device installed in the structural system to mitigate the wave-induced vibration. The method adopted in this study is a scheme similar to the one by updating the geometry of the structural system during the calculation of each time step, which is also called the coordinate moving frame approach. It is found from the analytical results that an offshore template structure enhanced with VE damper has better performance on its dynamic responses., The mitigation on the response amplitude is significant and the resonant vibration coinciding to the fundamental frequency of the structural system can be mitigated into a very small value after a few cycles of vibration.

I. INTRODUCTION

As the exploitation for the ocean resources, particularly, the energy related conservations is becoming more and more important with regard to the skyrocketing high price of petroleum lately, a more stable offshore platform system on which all kinds of machinery could be operated more safely and smoothly is drawing more attentions now. Although the offshore structure has been widely applied for the petroleum exploitation for many decades, however, the analysis for responses subject to dynamic forces mainly induced from random waves in the ocean is still a difficult task. The challenging issues for an offshore platform structural system in the ocean environment include material fatigues, strong heaving, surging and rolling vibrations, corrosion induced weakness in structural members, and stability requirements for the appropriate functioning of equipment on board.

Many efforts trying to solve some of these problems have been made lately, such as studies for the mitigation of the offshore platform systems [5, 6, 12], studies for the interactions between marine waves and floating offshore platform systems [9, 10] and studies trying to find an effective way for the dynamic analysis of offshore structures [3, 4]. For the mitigation of offshore structures including both the tension-leg type [11] and the template platform type, a series of studies have been performed in the later researches. An offshore template structural system, usually constructed with steel-frame and pile-columns fixed to the sea bed, has been widely applied to the middle-depth ocean exploitation. When the ocean waves exerting on the frames and platform of the template structure, the structure vibrates along with the exciting forces and then induces the damage of the system. To mitigate the wave induced vibration, a design by using mechanical damping system was proposed and an analytical method corresponding to was also derived [12]. Methods of time domain analysis and stochastic analysis [5] were both developed. The damper systems of various types were also applied and studied [6]. In those series of studies, the finite element method was utilized for time-domain analysis and only single case was applied to the example analysis. It was found that the nonlinear large deformation behavior is difficult to simulate by using finite element method when a small deformation is usually adopted for the derivation of most finite element methods.

The vector form intrinsic finite element method (VFIFE) was firstly developed by Ting, Shi and Wang in 2004 by adopting the traditional co-rotational explicit finite element method to improve the solution procedure for the mechanic problems [16]. As we know, the development of traditional co-rotational explicit finite element method has been over three decades. In 1973 Belyschko and Hsieh first established the theoretical foundation for the co-rotational explicit finite element method [1]. In 1993, Rice and Ting revised the tra-

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ditional co-rotational explicit finite element method to adopt an updated geometry during the calculation for the structural members [14, 15], which allows a large deformation problem to be observed. Lately a solution procedure by adapting the plane-frame element of VFIFE method has been developed in cooperating with the effect of the wave motions interacting with the offshore structure [2]. In that study, the verification for the solution accuracy of VFIFE method applied to offshore structure was performed and compared to the results from both the traditional finite element method and exact solutions. Efficiency of computation was also examined and found to be satisfied from the CPU-time cost in the computation.

In order to take the advantage of the VFIFE that is easily to be applied for the nonlinear problem, a solution procedure is further developed in this study to include the behavior of visco-elastic (VE) material, which is a typical nonlinear, anelastic material commonly utilized to absorb the input energy induced from the excitation sources. Following the previous study, a plane frame element derived from vector form intrinsic finite element method is adapted and applied to an offshore template platform subject to wave forces and furthermore, this vector form intrinsic finite element is modified in advance to incorporate a VE material, which with good energy-absorption ability is manufactured into a damping device installed in the structural system to mitigate the wave-induced vibration.

During the analysis for the typical template offshore structures, three cases of structural system are studied. The first case is a single-bay steel template structure, the second case is a double bay and the third case is a double bay template structure of which the size of span is reduced into half of the original one. In each case of analysis, two important structural features are taken into consideration, namely, the additional steel bracings and the installation of damping devices. The analysis is focused on the response reduction effect from either a steel-bracing or damping devices installed in the system. Therefore, firstly, a frame structural system without any bracing or damping device is considered. Then the frame with a single diagonal bracing and a double cross bracing are both studied. Finally, the bracings are replaced by damping devices. The responses of the structure corresponding to the variation of the structural system are calculated and compared against the one without any reinforcements or damping devices for the system. It is found that the application of VE damping system can reduce the vibration of the offshore structure effectively, particularly for the vibration in the frequency range resonant to the fundamental frequency of the structural system.

II. FUNDAMENTAL THEOREM FOR VFIFE METHOD

The fundamental theorems of vector form intrinsic finite element method are briefly introduced in this section [16].

1. Basic Assumption and Discretization

For a structural system constituted of deformable continuum media and joints, each structural member may change its geometrical dimensions and shapes when subject to external forces. Assuming that Newton's law is followed by the continuum and the distribution of mass is lumped at joints and represented as m_α^* on joint α at time t while the element between two joints is assumed to be mass-less, the equation of motion for this particular joint subject to a displacement vector $\Delta d_\alpha(t)$ is given as

$$m_\alpha^* \Delta \ddot{d}_\alpha(t) = F_\alpha^{ext} - F_\alpha^{int} \tag{1}$$

where F_α^{ext} is the external force acting on joint α while F_α^{int} is the internal resistance force vector reacted from the continuum itself.

Now following the discretization procedure applied in the finite element method, the continuum is divided into numerous appropriate sub-regions or elements. The prescribed boundary conditions of known exerted forces or displacements on the boundaries are generally applied. However, boundary conditions on the moving boundary between two interacted continuums including the consistence of displacement and the force equilibrium can also be taken into account.

2. Geometry of Co-rotational Coordinate

In the Bernoulli's beam theory, when the dimension of cross section of the member is much smaller compared to the length of the member (the 3rd dimension) it is assumed that the cross section remained plane after the deflection of the member. The displacement of each point in the plane coordinate system can be presented as a vector with horizontal and vertical components, u and v as

$$\bar{u} = \begin{Bmatrix} u \\ v \end{Bmatrix} \tag{2}$$

Now assuming that the displacement of the elements can be divided into two components, namely, the rigid body displacement and deformation displacement, the element is shown as a line element representing the neutral axis of the frame member. As shown in Fig. 1 for a frame element (1, 2) at time $t = 0$, it is a straight line. At time t, after the deformation, point A of the element deformed into A' on coordinate x' and therefore, the relative displacement vectors $d\bar{u}$ in terms of the rigid-body component $d\bar{u}^r$ and deformation component $d\bar{u}^d$ can be presented by the projection of position of A' on the coordinate $\hat{x}$ as $\hat{A}$, where the superscript r denotes rigid body and d denotes deformation component of the relative motion. For a small segment of the member the deflection is small and therefore, the frame element can be simplified into a line-segment connected between two nodes as shown in Fig. 2.

Assuming that the origin of the co-rotational coordinate is at node 1, $\hat{x}$ passes through node 2 and u_1 is parallel moved

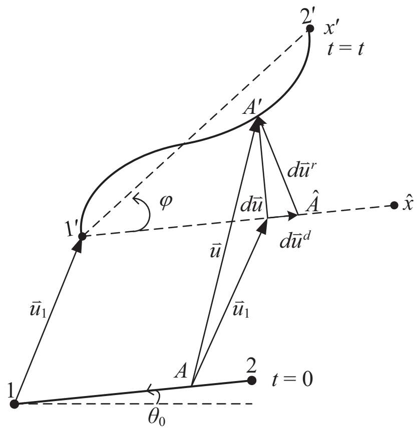

Fig. 1. The deformation and displacement of a plane frame element [16].

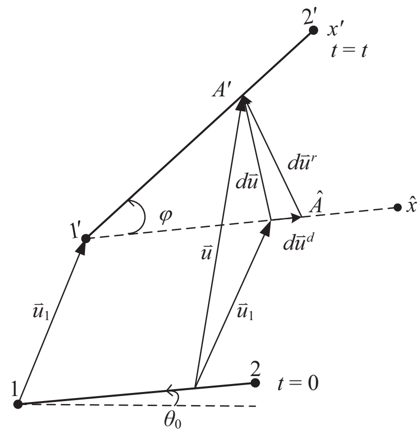

Fig. 2. The simplified deformation and displacement of a plane frame element.

from the element, the relative displacement vector of arbitrary point on the frame element *A* can be presented as

$$d\bar{u} = \bar{u} - \bar{u}_1 \tag{3}$$

Similarly, the relative rigid body displacement vector and relative deformation displacement vector of point A are as follows:

$$d\bar{u}^r = \bar{u}^r - \bar{u}_1^r = \bar{u}^r - \bar{u}_1 \tag{4a}$$

$$d\bar{u}^d = \bar{u}^d - \bar{u}_1^d = \bar{u}^d \tag{4b}$$

Then the relative displacement vector of arbitrary point on the frame element *A* is composed of the rigid body and deformation components as

$$d\bar{u} = d\bar{u}^d + d\bar{u}^r \tag{5}$$

The rigid body component and deformation component of the relative displacement are further presented in a matrix form, respectively, as

$$d\bar{\mathbf{u}}^r = \begin{Bmatrix} d\hat{u}^r \\ d\hat{v}^r \end{Bmatrix} = \left(\mathbf{R}^T - \mathbf{I}\right)\begin{Bmatrix} x' \\ 0 \end{Bmatrix} = \begin{Bmatrix} x'\left(\cos\phi - 1\right) \\ x'\sin\phi \end{Bmatrix} \tag{6}$$

$$d\bar{\mathbf{u}}^d = \bar{\mathbf{u}}^d = \begin{Bmatrix} \hat{u}^d \\ \hat{v}^d \end{Bmatrix} = d\bar{\mathbf{u}} - d\bar{\mathbf{u}}^r = \begin{Bmatrix} d\hat{u} \\ d\hat{v} \end{Bmatrix} - \left(\mathbf{R}^T - \mathbf{I}\right)\begin{Bmatrix} x' \\ 0 \end{Bmatrix} \tag{7}$$

where

$$\mathbf{R} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \tag{8}$$

If the time increment is from t to $t + \Delta t$ and the orientation angle is increased from θ to $\theta + \Delta\theta$, the rotational matrixes become

$$\hat{\mathbf{R}} = \begin{bmatrix} \cos\left(\Delta\theta\right) & \sin\left(\Delta\theta\right) \\ -\sin\left(\Delta\theta\right) & \cos\left(\Delta\theta\right) \end{bmatrix} \tag{9}$$

By using the co-rotational matrix to obtain displacement, the independent variables of displacement are simplified and presented as

$$\hat{\mathbf{d}}^* = \begin{Bmatrix} \Delta \\ \theta_1 \\ \theta_2 \end{Bmatrix} \tag{10}$$

where Δ is the longitudinal deformation of the element; θ_1 and θ_2 are rotations at two nodes after the rigid body motion is eliminated.

3. Formulation of the Internal Nodal Forces

The virtual work theorem is applied to the calculation for the energy conservation of the system such that the virtual works from the internal forces and external forces are balanced each other. The internal resistant force is, similarly, composed of two components of deformation and rigid-body, and the deformation component is the function of $\hat{x}$. To satisfy the equilibrium for the internal forces in the theorem of VIFIFE, the internal forces are solely related to the deformation components without taking account of the rigid body components. In the case of two-node frame element, instead of six degree of freedom of traditional beam element, only three independent parameters are required for the shape function. The longitudinal deformation is assumed to be a linear function deformed along the neutral axis as

$$\hat{u}_m^d = a_1 + a_2\hat{x} \tag{11}$$

After the substitution of the boundary conditions of the element, the coefficients are found as $a_1 = 0$ and $a_2 = \Delta/l$ and the shape function is written as

$$\hat{u}_m^d = s\Delta \tag{12}$$

where $s = \hat{x}/l$. The transverse deflection of the element is assumed to be a cubic algebraic function as

$$\hat{v}^d = a_3 + a_4\hat{x} + a_5\hat{x}^2 + a_6\hat{x}^3 \tag{13}$$

Similarly, after the substitution of boundary conditions of the element, the coefficients are ready to be found and the shape function of deflection is further written as

$$\hat{v}^d = \left(s - 2s^2 + s^3\right)l\theta_1 + \left(-s^2 + s^3\right)l\theta_2. \tag{14}$$

According to the simple beam theory, the longitudinal deformation at arbitrary point in the beam is presented as

$$\hat{u}^d = \hat{u}_m^d - \hat{y}\frac{d\hat{v}^d}{d\hat{x}} \tag{15}$$

After the substitution of (12) and (14), the longitudinal deformation at arbitrary point in the beam becomes

$$\hat{u}^d = \hat{u}_m^d - \frac{\hat{y}}{l}\frac{d\hat{v}^d}{ds} = s\Delta - \left\{\left(1 - 4s + 3s^2\right)\theta_1 + \left(-2s + 3s^2\right)\theta_2\right\}\hat{y} \tag{16}$$

The axial strain of the frame element then is obtained as

$$\hat{\varepsilon}_x = \frac{d\hat{u}^d}{d\hat{x}} = \frac{1}{l}\frac{d\hat{u}^d}{ds} = \frac{1}{l}\left\{\Delta - \left[\left(-4 + 6s^2\right)\theta_1 + \left(-2 + 6s\right)\theta_2\right]\hat{y}\right\} \tag{17}$$

In the matrix form the normal strain then becomes

$$\hat{\varepsilon}_x = \mathbf{B}\hat{\mathbf{d}}_e = \frac{1}{l}\left\{1 \quad (4 - 6s)\hat{y} \quad (2 - 6s)\hat{y}\right\}\begin{Bmatrix}\Delta \\ \theta_1 \\ \theta_2\end{Bmatrix} \tag{18}$$

According to the virtual work formulation, the internal virtual work of the element is done by the internal nodal forces and in terms of the axial strain and stress, the virtual work is presented as

$$\delta U_e = \delta d_e^T f_e^{\text{int}} = \int_{\hat{V}_e} \delta\hat{\varepsilon}_x^T \sigma_x d\hat{V} \tag{19}$$

For a small deformation, $\hat{V}_e \cong V_0$ and $d\hat{V} \cong dV_0$, after the substitution of the axial strain and the integration of the volume, the virtual work becomes

$$\delta U_e = \delta\hat{\mathbf{d}}_e^{*T}\int_{V_0}\delta\mathbf{B}^T\hat{\sigma}_x dV_0 = \delta\hat{\mathbf{d}}_e^{*T}\hat{\mathbf{f}}_e^* \tag{20}$$

where $\hat{\mathbf{f}}_e^*$ represents the internal force vector such as

$$\hat{\mathbf{f}}_e^* = \begin{Bmatrix}\hat{f}_{2x} \\ m_{1z} \\ m_{2z}\end{Bmatrix} = \int_{V_0}\delta\mathbf{B}^T\hat{\sigma}_x dV_0 \tag{21}$$

It is also noticed that the deformation displacement components $\left(\hat{u}^d, \hat{v}^d\right)$ and the axial strain $\hat{\varepsilon}_x$ may present a total deformation from $t = 0$ to $t = t$, or an incremental deformation from $t = t$ to $t = t + \Delta t$. Knowing that $dV_0 = ds\int dA$ and $\hat{\sigma}_x = E\hat{\varepsilon}_x = E\mathbf{B}\hat{\mathbf{d}}_e^*$ we can have

$$\hat{\mathbf{f}}_e^* = \frac{E}{l}\left(\int_0^1\begin{bmatrix}A & 0 & 0 \\ 0 & I(4-6s)^2 & I(4-6s)(2-6s) \\ 0 & I(4-6s)(2-6s) & I(4-6s)^2\end{bmatrix}ds\right)\begin{Bmatrix}\Delta \\ \theta_1 \\ \theta_2\end{Bmatrix} \tag{22}$$

After applying the equilibrium at the nodes, the internal nodal forces are obtained for a typical beam-frame member as

$$\hat{\mathbf{f}}_e^{\text{int}}\begin{Bmatrix}\hat{f}_{1x} \\ \hat{f}_{1y} \\ m_{1z} \\ \hat{f}_{2x} \\ \hat{f}_{2y} \\ m_{2z}\end{Bmatrix} = \begin{Bmatrix}-(AE/l)/\Delta \\ \left(6EI/l^2\right)(\theta_1 + \theta_2) \\ (2EI/l)(2\theta_1 + \theta_2) \\ (AE/l)/\Delta \\ -\left(6EI/l^2\right)(\theta_1 + \theta_2) \\ (2EI/l)(\theta_1 + 2\theta_2)\end{Bmatrix} \tag{23}$$

III. MODELING OF VISCO-ELASTIC MATERIAL IN VFIFE ELEMENT

When a visco-elastic (VE) material subjects to exciting forces, it will behave in a nonlinear large deformation. The up-loading and down-loading route in the force-deformation relationship of VE material are symmetric to each other with respect to the initial elasticity line. Presented in Fig. 3 is a typical relationship between force and deformation for the VE material subject to a harmonic excitation force. It shows that for each cycle of loading, the material will deform following the up-loading stress, resume to its un-loaded status and then again deform in the other way following the down-loading stress. During these cycles of loading, input energy is dissipated into heat. In this way the responses of structural system subject to exciting force can be mitigated through a device manufactured with VE material.

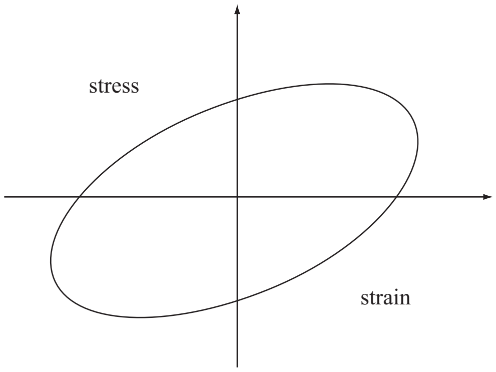

Fig. 3. The stress-strain relationship for a typical VE material.

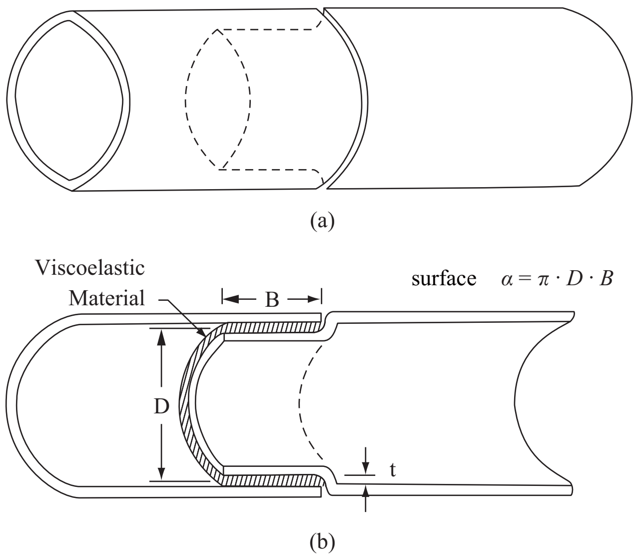

Fig. 4. A schematic view for a design of pipe-type VE damper [12].

According to previous studies [12], a typical damper by using a pair of pipes coupled together with VE material layered between them to absorb the shear energy induced from the relative motion are shown in Fig. 4. When the thin layer of VE material subjects to a shear stress at time-step $n\Delta t$, it strains such as

$$\varepsilon(n\Delta t) = \frac{1}{b}\bar{u}(n\Delta t) \tag{24}$$

where b is the thickness of the layer of VE material and $\bar{u}$ is the relative displacement between upper and lower face of the layer of VE material.

By adapting the constitutive formula for VE material as was derived by Lee and Tsai [7, 8], which is based on the molecular theory and the fractional derivative model and modified with available experimental results, for the linear variation of the relative displacement $\bar{u}$ between two time steps, $(n-1)\Delta t$ and $n\Delta t$, the stress at time step $n\Delta t$, is presented as

$$\sigma(n\Delta t) = \left[G_0 + \frac{G_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}\right]\frac{1}{b}\bar{u}(n\Delta t) + \sigma_p(n\Delta t) \tag{25}$$

where G_0 and G_1 represent shear modulus corresponding to storage and dissipation of energy, respectively; Γ is the gamma function; α is a fractional number corresponding to the fractional derivative applied to the formulation and $\sigma_p(n\Delta t)$ is the previous time effect of the strain.

The properties of shear modulus G_0 and G_1 are sensitive to both the strain energy absorbed by the material and the variation of ambient temperatures. By calibrating from experimental testing data, the module corresponding to the dissipation and storage of energy during the deformation of a VE material are mostly equal to each other and therefore, presented as [7, 8]

$$G_0 = G_1 = A_0 \exp\left[\beta_1 \Delta T + \beta_2 |\Delta T| + \beta_3 \operatorname{sgn}(\Delta T)\right] \cdot \left[1 + B_0 \exp\left(-\beta \int \sigma d\varepsilon\right)\right] \tag{26}$$

where B_0 and β are coefficients corresponding to the strain energy absorbed by the material; A_0 is the original shear modulus and β_1, β_2 and β_3 are parameters corresponding to the variation of ambient temperatures.

The previous time effect of the strain $\sigma_p(n\Delta t)$ is further presented as

$$\sigma_p(n\Delta t) = \frac{E_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}\left(W_0^n \varepsilon(0) + \sum_{i=1}^{n-1} W_i^n \varepsilon(i\Delta t)\right) \tag{27}$$

where W_0^n and W_i^n are weighting functions presented into a form with respect to time steps as

$$W_0^n = (n-1)^{1-\alpha} + (-n+1-\alpha)\cdot n^{1-\alpha} \tag{28a}$$

$$W_i^n = -2(n-i)^{1-\alpha} + (n-i+1)\cdot n^{1-\alpha} + (n-i-1)^{1-\alpha} \tag{28b}$$

Now for a layer of VE material with surface area a, the resultant force $\bar{F}(n\Delta t)$ at time-step $n\Delta t$ from the deformation $\bar{u}(n\Delta t)$ is ready to be obtained and given as

$$\bar{F}(n\Delta t) = a\sigma(n\Delta t) = \frac{a}{b}\left[G_0 + \frac{G_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}\right]\bar{u}(n\Delta t) + a\sigma_p(n\Delta t) \tag{29}$$

Since in the VIFIFE method, the explicit variable of the formulation is force, the above relationship between force and deformation can be applied to the equation of motion for the structural system directly.

IV. THE INCORPORATION OF VE DAMPING DEVICES IN THE OFFSHORE STRUCTURE

The dynamic equations of motion for an engineering structural member element with mass **M** and damping **C** subject to the waves propagating in the normal direction of the structural member, can be written as

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} = \mathbf{F}_w - \mathbf{F}_{\text{int}} \tag{30}$$

where $\ddot{\mathbf{d}}$ and $\dot{\mathbf{d}}$ are the acceleration and velocity vectors of the structural members respectively. The external force $\mathbf{F}_w$ is obtained from the integration of wave pressure over the normal surfaces of the submerged structural member after taking account of the relative motions between the structural member and waves and presented as

$$\mathbf{F}_w = \int_{-d}^{0} d\mathbf{f}_w$$

$$= \int_{-d}^{0}\left[\rho_w C_m \frac{\pi D^2}{4}(\dot{\mathbf{u}}_w - \ddot{\mathbf{d}}) + \frac{1}{2}\rho_w C_d D\left|\mathbf{u}_w - \dot{\mathbf{d}}\right|(\mathbf{u}_w - \dot{\mathbf{d}})\right] dS \tag{31}$$

where ρ_w is the water density; C_m and C_d are coefficients corresponding to inertia and form drag effect respectively; $\dot{\mathbf{u}}_w$ and $\mathbf{u}_w$ are the acceleration and velocity of the fluid normal to the structural member resulted from the wave motions; D is the diameter of the structural members. The nonlinearity of the drag term may be retained through the use of the approximate relationship derived by Penzien and Tseng [13].

For the simulation of waves, a small amplitude wave, which is generally applied for the engineering purposes, is also used in this study by assuming that the fluid is inviscous, irrotational and incompressible. Based on the presumptions, the equation of motion as the Laplace equation is shown as follows

$$\nabla^2\varphi = 0 \tag{32}$$

where φ is the velocity potential as

$$\phi = \frac{\pi H}{kT}\frac{\cosh ky}{\sinh kh}\sin(kx - \omega t) \tag{33}$$

in which H is the wave height, L the wave length, h the water depth and k as the wave number. The angular frequency ω is presented in the dispersion equation as

$$\omega^2 = gk \tanh kh \tag{34}$$

Under the velocity potential, the corresponding horizontal and vertical velocities are given, respectively, by

$$u_w = \frac{\pi H}{T}\frac{\cosh ky}{\sinh kh}\cos(kx - \omega t) \tag{35a}$$

$$v_w = \frac{\pi H}{T}\frac{\sinh ky}{\sinh kh}\sin(kx - \omega t) \tag{35b}$$

After the integration of the wave force as shown in (31), by combining the inertial effect of the displaced volume of water and the damping terms as a modified mass $\mathbf{M}^*$ and damping $\mathbf{C}^*$, the equation of motion for the whole offshore structural system becomes

$$\mathbf{M}^*\ddot{\mathbf{d}}_{\boldsymbol{\alpha}} + \mathbf{C}^*\dot{\mathbf{d}}_{\boldsymbol{\alpha}} = \rho C_m \forall \dot{\mathbf{u}} + \frac{1}{2}\rho C_d A\left|\mathbf{u}_{\mathbf{w}}\right|\mathbf{u}_{\mathbf{w}} - \mathbf{F}_{\boldsymbol{\alpha}}^{\text{int}} \tag{36}$$

where $\mathbf{M}^* = \mathbf{M} + \mathbf{m_a}$, $\mathbf{m_a}$ is the added mass from the water and $\mathbf{C}^* = \mathbf{C} + \mathbf{C}_h$ is a combination of structural damping and the hydraulic damping $\mathbf{C}_h$ due to the drag effect between the water and structural members.

When the VE damping devices are installed in the offshore structural system, the equation of motion becomes

$$\mathbf{M}^*\ddot{\mathbf{d}}_\alpha + \mathbf{C}^*\dot{\mathbf{d}}_\alpha = \rho C_m \forall \dot{\mathbf{u}} + \frac{1}{2}\rho C_d A\left|\mathbf{u}_{\mathbf{w}}\right|\mathbf{u}_{\mathbf{w}} - \mathbf{F}_\alpha^{\text{int}} - \bar{\mathbf{F}}_\alpha \tag{37}$$

where the damped forces from the VE material $\bar{\mathbf{F}}_\alpha$ are presented as

$$\bar{\mathbf{F}}_\alpha = \begin{Bmatrix} -\left\{\frac{a}{b}\left[E_0 + \frac{E_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}\right]\Delta + a\sigma_p\right\} \\ \left(6EI/l^2\right)(\theta_1 + \theta_2) \\ (2EI/l)(2\theta_1 + \theta_2) \\ \frac{a}{b}\left[E_0 + \frac{E_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}\right]\Delta + a\sigma_p \\ -\left(6EI/l^2\right)(\theta_1 + \theta_2) \\ (2EI/l)(\theta_1 + 2\theta_2) \end{Bmatrix} \tag{38}$$

Now by solving (37) along with (38) through VFIFE method the responses of an offshore template structure with enhancement of dynamic characteristics by either using a steel-bracing system or the installation of a VE damper system can be obtained.

V. ANALYTICAL RESULTS AND DISCUSSION

In the numerical analysis of the VFIFE method applied to the offshore structure, both the accuracy and efficiency of the VFIFE method applying to the typical structures were examined and verified in previous studies [2]. In this study, the

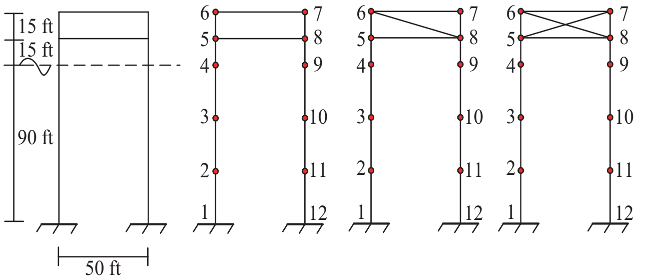

Fig. 5. A one-bay template offshore structure with single, double bracings and dampers.

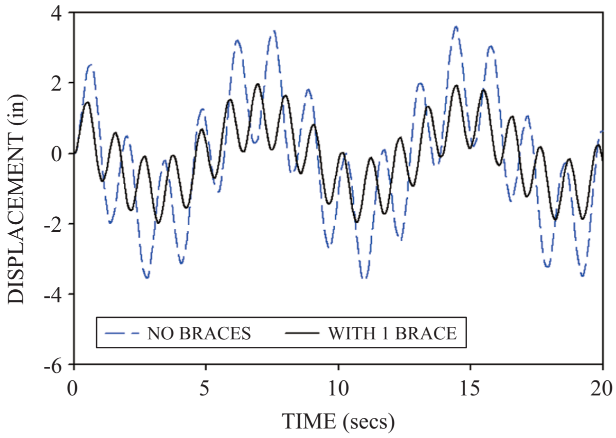

Fig. 6. Comparison of the lateral displacement for a single bracing template structure.

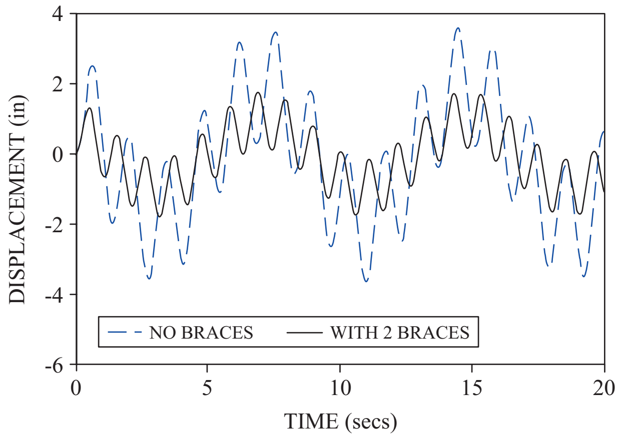

Fig. 7. Comparison of the lateral displacement for a double bracing template structure.

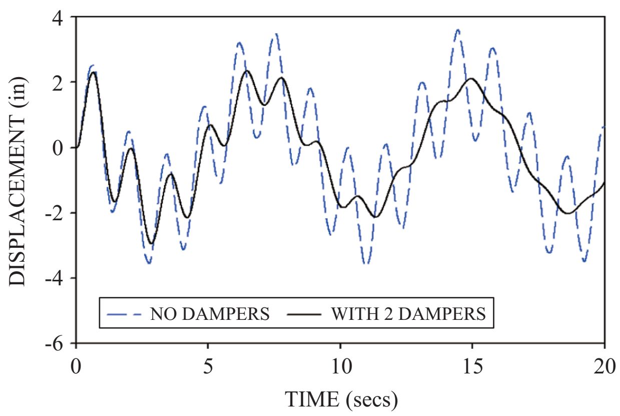

Fig. 8. Comparison of the lateral displacement for VE damper installed in the upper frame.

applicability of the analytical method for the VE material and the effect for the response mitigation of offshore structures incorporated with a VE damping system are both examined and also compared with the very same structural system reinforced with steel-bracings. Therefore, for offshore structure simulation, three cases of template offshore structures are designed, namely, a simple single bay template frame, a double-bay template frame and a double-bay template frame with reduced size of span.

Typical normal storm conditions are assumed for the waves applied to the offshore template structures under analysis as: 20 ft (6.10 m) of wave height; 300 ft (91.44 m) of wave length and 280 ft (85.34 m) of water depth. The periods of the assumed wave under normal storm condition is also identified as 7.65 seconds. The responses are compared to each other and against the responses of the original structural system without any structural enhancement.

1. Mitigation Effect on One-Bay Template Structure

In the first case of analytical example, a typical one-bay template offshore structure is shown in Fig. 5, where the upper frame of the structure is alternately reinforced with one steel-bracing and two bracings. And finally the bracings are replaced with VE dampers. The comparison for the displacement responses of the template structural system is made against the original one that has no bracings or dampers applied for mitigating the vibrations. The material property of elastic modulus is $E = 10^{11}$ psi, while the outer diameter and thickness are 4 ft and 1.5 in, respectively, for vertical members and 2 ft and 0.5 in for the horizontal and diagonal bracing members. The dimensions of structures and damping devices are also shown in the figure.

Shown in Figs. 6 and 7 are lateral displacement responses of the top deck of the offshore template structure subject to wave forces while reinforcing bracings of one-way and two-way are alternately applied in diagonal to the upper frame. Compared to the one without any bracings, the amplitude of displacement is reduced. Compared to one-bracing system as shown in Fig. 6, the two-bracing system (Fig. 7) has smaller responses but the reduction effect is not in linear relation to the number of bracings. The reduction effect from the diagonal bracings is mainly on the amplitudes of displacement along with the increase of frequency due to a stiffer structural system.

Presented in Fig. 8 is also a comparison of lateral dis-

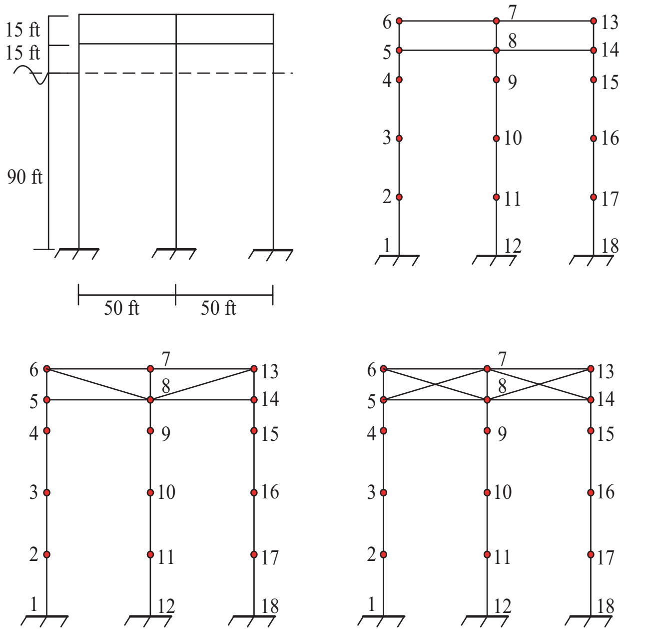

Fig. 9. A two-bay template offshore structure with single, double bracings and dampers.

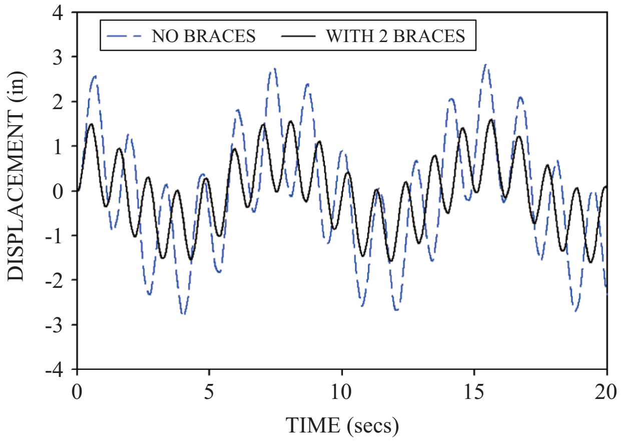

Fig. 10. Comparison of lateral displacement for a two-bay template structure with two single bracing.

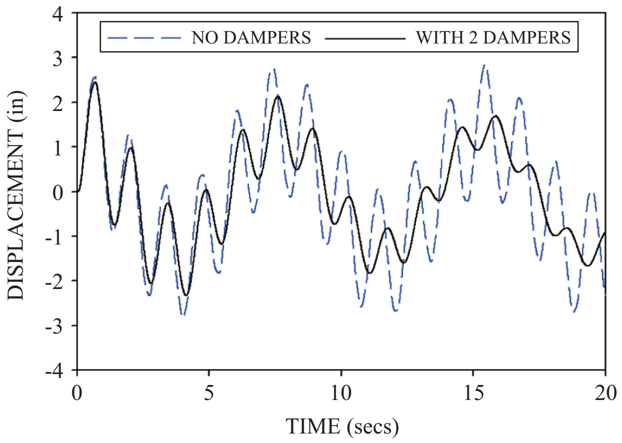

Fig. 11. Comparison of lateral displacement for a two-bay template structure with two diagonal VE.

placement responses for the offshore structure, where two VE damping devices are installed in the diagonal members for the upper frame. It is observed that for the first half cycle of the wave action, basically, the motion of the structure is complied with the wave motions, but after that the amplitude of displacement is reduced more and more significantly. Different from the case of enhancement of stiffness that the structure is reinforced with diagonal bracings, the reduction of the displacement due to the application of VE damper is gradual and mainly on the vibrations of high frequency range. It is identified that the high frequency motion mitigated by the VE damping devices is corresponding to the properties of the structures.

2. Mitigation Effect on Two-Bay Template Structure

In the second case of analytical examples, a typical two-bay template offshore structure is also shown in Fig. 9, where similarly, the upper frames of the structure are alternately reinforced with a single diagonal bracing and a cross double-bracings. And then, these two types of diagonal bracing are replaced with either a single or double VE damper, alternately. The comparisons for displacement responses of the template structural system against the one without any bracings or dampers applied for mitigating the vibrations are presented as follows.

Shown in Fig. 10 are lateral displacement responses of the top deck of the offshore template structure subject to wave forces while single diagonal bracings are applied to two upper frames. Alternately, these two single diagonal bracings are replaced by VE dampers and the responses of the same top deck are presented in Fig. 11. From the comparison of these two figures, it is found that when a single bracing system is utilized for the upper frame, the reduction for the amplitude of responses is immediate and the maximum amplitude of response remains for the rest of responses. However, when the single bracing is replaced by a single VE damper, though the reduction effect on the response amplitude is not immediate, responses are gradually mitigated and eventually reduced to a small value, which is even smaller than that in the case of single diagonal bracing.

A similar phenomenon is also observed when two cross bracing system is applied and compared against the responses of structural system with replacement of bracings by VE dampers as shown in Figs. 12 and 13. Figure 12 shows the responses of template structure with double cross bracings on the upper frame while Fig. 13 shows the same responses of the structure but reinforced with VE dampers instead. The other phenomenon observed in the responses of template structure with VE dampers is that the vibration of the top deck eventually yields to the vibration-pattern of excitation force from the

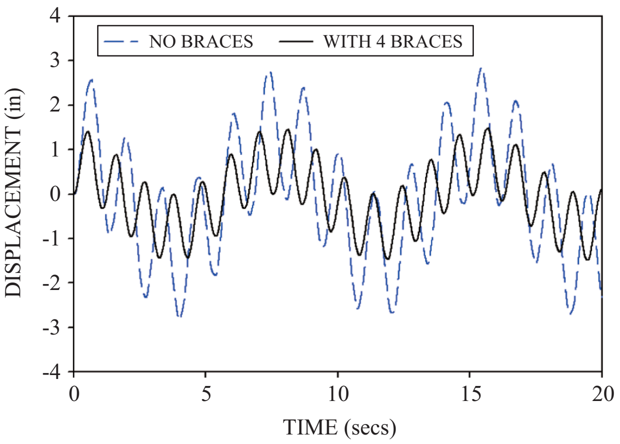

Fig. 12. Comparison of lateral displacement for a two-bay template structure with two diagonal VE dampers.

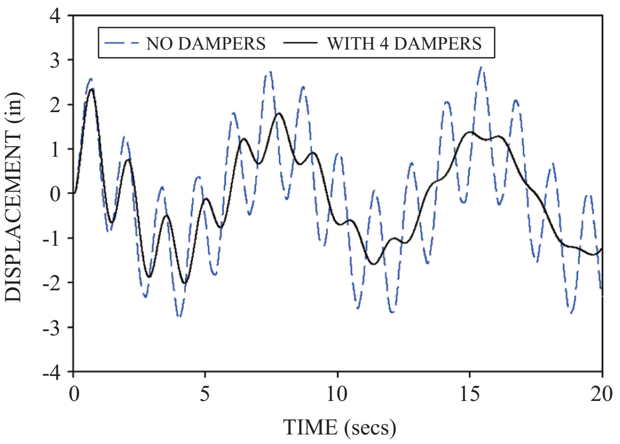

Fig. 13. Comparison of lateral displacement for a two-bay template structure with two diagonal VE dampers.

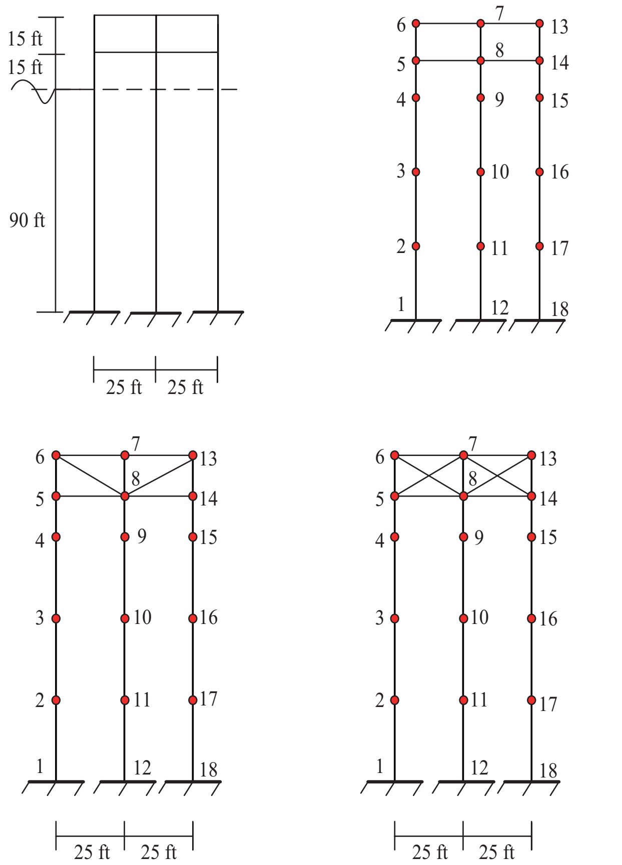

Fig. 14. A two-bay template offshore structure with a bay of half-span.

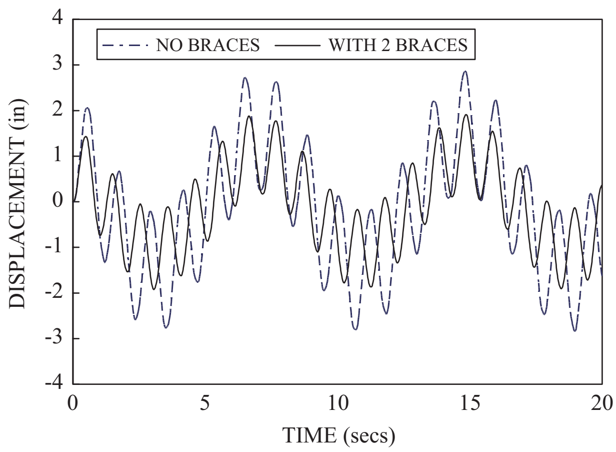

Fig. 15. Comparison of lateral displacement for a two-bay (half-size) template structure with two diagonal steel-braces.

waves. That means the damping effect works well for the resonant vibration near the fundamental frequency of the structure as is found in the one-bay case. While the vibration of high frequency is maintained for the structures reinforced with either a single or a double bracing systems. It is identified that the high frequency motion mitigated by the VE damping devices is related to the stiffness, mass and size of member of the offshore structures submerged in the water.

3. Comparison of Mitigation Effect for Template Structures with Various Bay Dimensions

In order to know the influence of bay-dimensions to the effect of VE-damper installed in the template structure, a two-bay offshore template structure with smaller size (one half of the original span) of bay-dimension is studied and shown in Fig. 14, where the upper frame of the structure is also alternately reinforced with a single and a double steel bracings. When compared with the frame analyzed in the case 1, it is a structure of same dimension but with an additional pile-column in the middle of the span. Therefore, the stiffness of this structure is a little higher and therefore, the response will be smaller. As shown in Figs. 15 and 16 are comparisons of lateral displacement responses of the top deck of the structure firstly reinforced with a one-way bracings in the upper frame and then replaced by a one-way VE dampers for the bracings, respectively. In the comparisons against the one without any bracing, the amplitudes of the displacements in both cases are

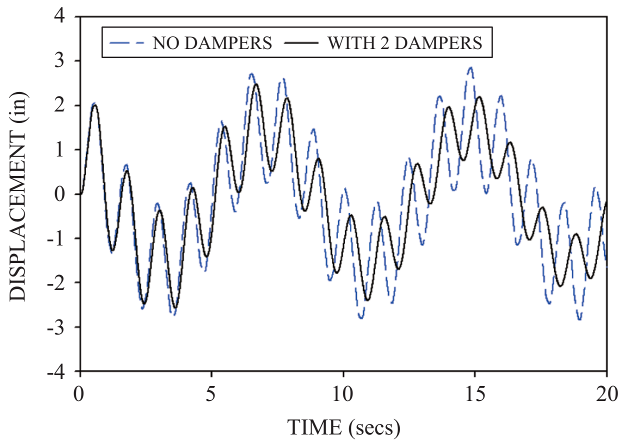

Fig. 16. Comparison of lateral displacement for a two-bay (half-size) template structure with two diagonal VE dampers.

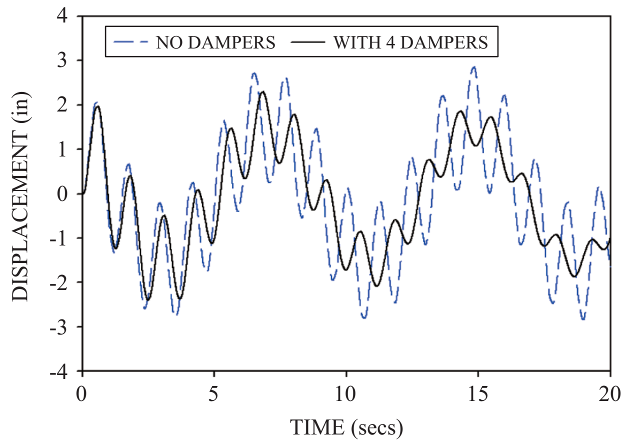

Fig. 18. Comparison of lateral displacement for a two-bay (half-size) template structure with four VE dampers.

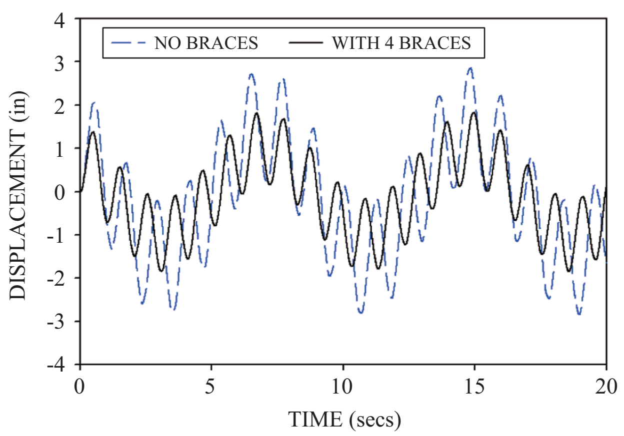

Fig. 17. Comparison of lateral displacement for a two-bay (half-size) template structure with four steel-braces.

greatly reduced. Figures 17 and 18 are responses for the two half-bay structure reinforced with a double bracing and a double damper system, respectively. Again, typical phenomena are observed for the difference of responses between a steel-braced structure and a damper enhanced structure.

For the structure reinforced with diagonal steel-bracings, the mitigation on the response may not effectively amplified by the increment in the number of bracings such as from a single (Fig. 15) up to a double bracing system (Fig. 16). However, the increment of VE dampers in the structural system could provide more effective mitigation on the responses as observed from the comparison of Figs. 16 and 18. It is also found that the installation of VE dampers in a one-bay structural system has better effectiveness on the vibration mitigation (Fig. 17) compared to a two-bay system with half-size of span (Fig. 18).

VI. CONCLUSIONS

In this study an analytical method by adopting the previous studies for the VFIFE numerical method applied to offshore structural analysis is developed to combine the VE damping device into the offshore structure. Several typical offshore template structures of one-bay and two-bay are also analyzed for the effectiveness of vibration mitigation due to the installation of VE dampers in the structural system. The mitigation effect due to the addition of diagonal bracings instead of the VE dampers to the offshore structural system is also studied. It is firstly concluded that the VFIFE method has good potential being a powerful analytical tool for the offshore structures, particularly when the large displacement and nonlinear approach are required in the analysis such as the inclusion of the VE material in this study.

It is observed from all of these response comparisons that for the offshore template structure, the addition of steel-bracings in the upper frame produces an evenly distributed reduction along the response time history that is a response with smaller amplitude but contains a higher frequency vibration mode. However, when the structure is enhanced in its damping characteristics with VE damper, the mitigation on the response amplitude takes place after half cycle of excitation but as time passes, the mitigation effect takes on more and more significantly. Eventually, the resonant vibration coinciding to the fundamental frequency of the structural system can be mitigated into a very small value.

In the comparison between two offshore template structures with same spans, in which one is two-bay structure with half-size of span (Fig. 10) and the other is one-bay with a whole span (Fig. 5), when the VE damping devices are applied, it seems that the one-bay structure may have better effectiveness for the vibration mitigation than two-bay structure of half-span. It is also found that when the steel-bracing system is applied, the double cross bracing may better reduce the amplitude of responses but the reduction effect only minor increased compared to a single diagonal bracing system to the structure.

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