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Application of Viscoelastic Damper in Offshore Structures

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ABSTRACT

The research described in this paper involves the development of techniques for new damping devices applied to typical offshore structural systems, and a method for time domain analysis on offshore structural systems incorporating nonlinear viscoelastic material. Mitigation of vibration and enhancement of dynamic performance for the offshore structural system were observed during the analysis. This investigation was performed for typical offshore structures subjected to wave forces induced by both harmonic and random type waves. The wave force was based on the Airy wave theory and Morison equation for a small body. Based on the Newmark method for nonlinear systems, a numerical method for analysis of offshore structures incorporating a viscoelastic damper is developed. After carrying out computation in the time domain, results of the vibration responses for the system with added dampers are used to evaluate the effect of the vibration mitigation. In the cases analyzed, it is found that the amplitude of the vibration of the structure can be reduced by up to one half compared to the original amplitude.

Key Words: offshore structure, dynamic analysis, viscoelastic damper, vibration mitigation

I. Introduction

When structures are subjected to dynamic loading such as wind loading, strong ground motions due to earthquakes, or wave forces for offshore structures, tremendous amounts of energy are input into the structural system and this usually causes excessive vibration and deflection. Then essential damage occurs in the structure. In order to mitigate vibration and then avoid serious damage, a new mechanical damping device, which has substantial energy absorption ability, was incorporated in the structural system. Well known cases consist of the World Trade Center in New York City and the Columbia Center in Seattle, where the devices are applied to reduce the vibration induced by wind loading (Keel and Mahmoodi, 1986). Experimental testing of the material properties has been carried out and has shown that viscoelastic dampers significantly improved the dynamic performance of the structures (Mahmoodi,1972; Bergman and Hanson, 1986; Lin *et al.*, 1988; Chang *et al.*,1991). According to the testing data, substantial energy input into the structural system was absorbed by this damping material.

Although the encouraging mechanical properties of the material were observed in the laboratory, it is usually difficult to obtain adequate evaluation and good design for a structural system when the mechanical behavior of the damping devices can not be predicted appropriately. To solve this problem, an analytical material model for this viscoelastic damper, which can accurately describe the mechanical behavior, were developed (Lee and Tsai, 1992, 1994). With this model evaluations for some typical structural systems associated with damping devices were performed (Tsai and Lee, 1992a, 1992b, 1993a, 1993b), and good results in dynamic performance were obtained.

It is well known that, typical environmental loading applied to offshore structures such as wind, surface waves and strong currents during severe storms, usually cause significant vibrations. Severe deflections and deformations occur subsequently and result in structural damage. The template structure is a common type of infra-structure widely used in engineering structures in marine environments, such as petroleum production complexes, radar stations, and other facilities for navigation or military purposes. A major concern is pollution of the marine environment due to the collapse of or severe damage to a petroleum complex, where a great amount of petroleum is usually stored when it is far away from shore. Damage caused by all of these dynamic loading in offshore structures is usually substantial. Therefore, it is believed that application of viscoelastic dampers to offshore structures may greatly enhance the structural dynamic performance.

Therefore, in this study, a typical template structure was selected and analyzed when subjected to marine environmental loading of both harmonic and random types. The wave force was based on the Airy wave theory and Morrison equation for small body. For random type waves, the Pierson-Moskowitz spectrum was used to generate the wave force spectrum; then, the wave force time history using the Monte Carlo method as a homogeneous Gaussian random process with zero mean was obtained. Since this was the first stage of the investigation, a simplified equivalent single degree of freedom system was utilized to simulate the offshore structural system. The purposes of this study were to develop an appropriate method for nonlinear dynamic analysis of the system, and to determine the vibration mitigation effect when damping devices were applied to a system located in a marine environment.

II. Analytical Model of the Damper

In order to adequately predict the behavior of a structural material subjected to dynamic loading, an analytical model must be capable of representing the typical material characteristics and adequately describing the dynamic behavior. Based on molecular theory and the fractional derivative viscoelastic model (Bagley and Torvic, 1979; Bagley, 1983), a nonlinear analytic model was derived and modified by using the available experimental results by Lee and Tsai (1992, 1994). In this new developed nonlinear model, the constitutional formula, having a fractional derivative form, is presented as

$$\sigma(t)=E_0\varepsilon(t)+E_1D^{\alpha}(\varepsilon(t)),\ 0<\alpha<1, \tag{1}$$

where σ and ε are the stress and strain of the material, and E_0 and E_1 represent the elastic modulus corresponding to the storage and the loss energy, respectively. In this model, the modulus degradation and the thermal effect are taken into consideration. Corresponding to a temperature difference $\Delta T=T-T_0$ from the referred temperature T_0, the material elastic moduli are given by

$$E_0=E_1=A_0\exp[\beta_1\Delta T+\beta_2|\Delta T|+\beta_3\mathrm{sgn}(\Delta T)]$$
$$\bullet[1+B_0\exp(-\beta\int\sigma d\varepsilon)], \tag{2}$$

where B_0 and β are coefficients to account for the energy absorption ability of the material; A_0 is the coefficient corresponding to the original modulus of the material; and β_1 to β_3 are coefficients corresponding to the thermal effect. All of these unknown coefficients are material-dependent and determined by the experimental data. The fractional derivative is, accordingly, presented as

$$D^{\alpha}(\varepsilon(t))=\frac{1}{\Gamma(1-\alpha)}\frac{d}{dt}\int_0^t\frac{\varepsilon(t)}{(t-\tau)^{\alpha}}d\tau,\ 0<\alpha<1, \tag{3}$$

where $\Gamma(1-\alpha)$ is the gamma function.

To apply the fractional derivative model to the time-domain analysis, a numerical scheme using the finite element method is proposed. For the linear variation of the strain between two time steps, $(n-1)\Delta t$ and $n\Delta t$, the strain is given by

$$\varepsilon(t)=(n-\frac{\tau}{\Delta t})\,\varepsilon[(n-1)\Delta t]+[\frac{\tau}{\Delta t}-(n-1)]\,\varepsilon(n\Delta t),$$
$$(n-1)\Delta t\le\tau\le n\Delta t. \tag{4}$$

Subsequently, a constitutive law for the viscoelastic damper at time step $n\Delta t$ can be written as

$$\sigma(n\Delta t)=[E_0+\frac{E_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}]\,\varepsilon(n\Delta t)+\sigma_p(n\Delta t),$$
$$n\ge2. \tag{5}$$

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

$$\sigma_p(n\Delta t)=\frac{E_1\Delta t^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}(W_0^n\varepsilon(0)+\sum_{i=1}^{n-1}W_i^n\varepsilon(i\Delta t)),$$
$$n\ge2, \tag{6}$$

where W_0^n and W_i^n are weighting functions:

$$W_0^n=(n-1)^{1-\alpha}+(-n+1-\alpha)n^{-\alpha},$$

and

$$W_i^n=-2(n-i)^{1-\alpha}+(n-i+1)^{1-\alpha}+(n-i-1)^{1-\alpha}.$$

For a structural member with definite dimensions through integration, a relationship between the force F and the displacement x similar to Eq. (5), can be written as

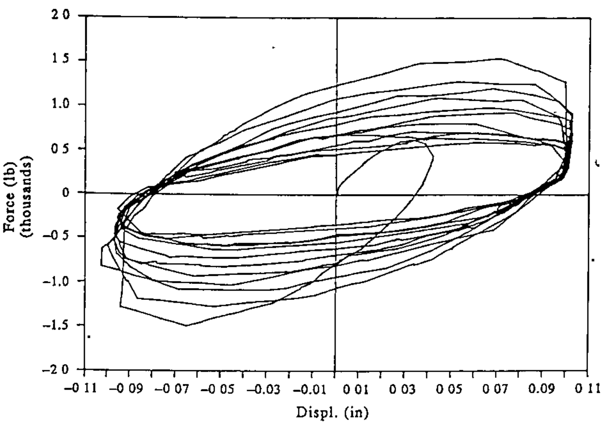
$$F(n\Delta t)=[K_0+\frac{K_1(\Delta t)^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}]\,x(n\Delta t)+F_p(n\Delta t), \tag{7}$$

where K_0 and K_1 are the stiffness corresponding to the storage and the loss factor for the viscoelastic damper, respectively. The previous time effect F_p is

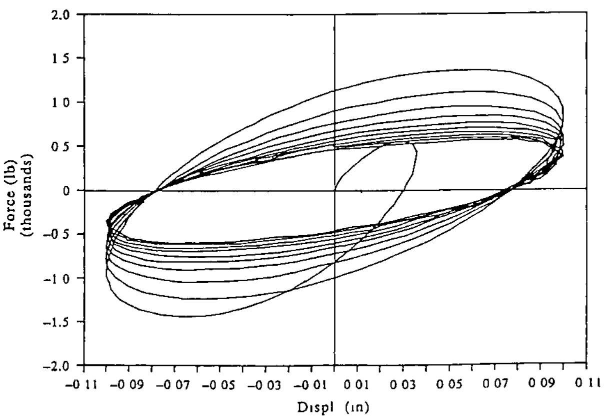
$$F_p(n\Delta t) = \frac{K_1 \Delta t^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)} [W_0^n x(0) + \sum_{i=1}^{n-1} W_i^n x(i\Delta t)], \quad \textbf{(8)}$$

where F and x are the force and the displacement, respectively.

A typical force-displacement relationship representing the mechanical behavior of the viscoelastic damper is shown in Fig. 1, where Fig. 1(a) represents the experimental data and Fig. 1(b) shows the results of analytical simulation from the model. It is observed that a great amount of energy can be absorbed during each cycle of hysteretic motion of the material, and that this mechanical behavior is adequately simulated by the analytical model.



(a)



(b)

Fig. 1. Force-displacement relationships for viscoelastic damper (after Lee and Tsai, 1992). (a) Experimental data. (b) Analytical results.

III. Incremental Form of the Equation of Motion

The dynamic equation of motion for the engineering structure with system mass M, structural damping C, and stiffness K, subjected to wave forces propagated in the normal direction of the structural members, can be written as (Newman, 1977; Sarpkaya and Isaacson, 1981)

$$(M + \rho C_a V)\ddot{x} + C\dot{x} + Kx$$
$$= \rho C_m V \ddot{u} + \tfrac{1}{2}\rho C_d A |\dot{u} - \dot{x}| (\dot{u} - \dot{x}), \quad \textbf{(9)}$$

where C_a=C_m−1; $(M$+$\rho C_a V)$ represents the structural system mass combined with the added mass; $\dot{u}$ and $\ddot{u}$ are the velocity and acceleration of the fluid; and $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the structural system. C_m and C_d are coefficients corresponding to the inertial and drag effect, respectively; V is the displaced volume of the structure, and A is the projected front area of the structural member. The last term in the equation representing the drag force due to the relative velocity of the fluid is nonlinear. When critical loading is caused by high-amplitude long-period waves giving rise to small amplification of response, the nonlinearity of the drag term is retained through use of the approximate relation (Penzien, 1978);

$$|\dot{u} - \dot{x}| (\dot{u} - \dot{x}) = |\dot{u}| \dot{u} - 2(\langle \dot{u} \rangle)\dot{x}\,, \quad \textbf{(10)}$$

where $\lhd \dot{u} \rhd = \hat{u}$ represents the time average of $|\dot{u}|$. Through substitution of Eq. (10) and by letting $\hat{u} = |\dot{u}|$ to further linearize the wave forces, Eq. (9) then becomes

$$(M + \rho C_a V)\ddot{x} + (C + \rho C_d A \lhd \dot{u} \rhd)\,\dot{x} + Kx$$
$$= \rho V C_m \ddot{u} + \tfrac{1}{2}\rho C_d A \hat{u}\dot{u}\,, \quad \textbf{(11)}$$

where $(C + \rho C_d A \lhd \dot{u} \rhd)$ represents the structural damping combined with the fluid damping.

1. Wave Force from Airy Theory for Small Amplitude Waves

If the Airy theory for small amplitude waves is applied, and a wave of height H, frequency ω, and wave number k in a water of depth d, are assumed, then the horizontal velocity of the fluid at joint $p(x_p,\ y_p)$ is expressed as

$$\dot{u} = E_p \cos(kx_p - \omega t); \quad \textbf{(12)}$$

thus the acceleration is obtained by the first time derivative as

$$\dot{u}=\omega E_p \sin(kx_p-\omega t), \tag{13}$$

where

$$E_p=\frac{\omega H}{2}\frac{\cosh ky_p}{\sinh kd}. \tag{14}$$

The force term on the right-hand side of Eq. (11) may be rewritten as

$$P(t)=K_m\dot{u}+K_d\hat{u}(t)u(t),$$

where K_m and K_d are given by

$$K_m=\rho C_m V,\ K_d=\frac{1}{2}\rho C_d A.$$

After substitution of Eqs. (12) and (13) into Eq. (14), the wave force in terms of small amplitude waves becomes

$$P(t)=E_p[K_d\hat{u}\cos(kx_p-\omega t)+K_m\omega\sin(kx_p-\omega t)]$$

$$=F_p\sin(kx_p-\omega t+\phi_p), \tag{15}$$

where

$$F_p=E_p[(K_d\hat{u})^2+(K_m\omega)^2]^{1/2},$$

and

$$\phi_p=Tan^{-1}(\frac{K_d\hat{u}}{K_m\omega}),\ 0\leq\phi_p\leq\pi/2.$$

2. Random Wave Force from Pierson-Moskowitz Spectrum

For generation of the random wave force, the Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964) is adopted here and written as

$$S_\eta(\omega)=\frac{2\pi\alpha g^2}{\omega^5}\exp(\frac{-B}{\omega^4}), \tag{16}$$

where $\alpha=8.1\times10^{-3}$ is the Phillip's constant, and $B=0.74g/U$ with the characteristic wind speed U over the water. If the Morison equation for a small body is again applied, that the wave force exerted on the structural member is that shown in Eq. (14), the wave force spectral density can then be expressed as (Borgman, 1967; Sarpkaya and Isaacson, 1981)

$$S_P(\omega)=\frac{8}{\pi}K_d^2\sigma_u{}^2S_u(\omega)+K_m^2S_{\dot{u}}(\omega), \tag{17}$$

where the velocity spectrum $S_u(\omega)$ and the acceleration spectrum $S_{\dot{u}}(\omega)$ obtained using the complex receptances $H_{\dot{u}}(\omega)$ and $H_u(\omega)$ are given by

$$S_{\dot{u}}(\omega)=|H_u(\omega)|^2S_\eta(\omega), \tag{18}$$

and

$$S_u(\omega)=|H_u(\omega)|^2S_\eta(\omega). \tag{19}$$

Now, with the wave force spectrum ready, a homogeneous Gaussian random process $P(t)$ with zero mean and spectral density $S_P(\omega)$ can be obtained by applying the Monte Carlo technique (Rice, 1954; Shinozuka, 1972). The random wave force time history is then expressed in a form of the sum of cosine functions:

$$P(t)=\sqrt{2}\sum_{j=1}^{N}A_j\cos(\omega_j t-\phi_j), \tag{20}$$

where

$$A_j=\sqrt{2S_P(\omega_j)\Delta\omega},$$

$$\omega_j=(j-\frac{1}{2})\Delta\omega,$$

and ϕ_j are random angles distributed uniformly between 0 and 2π.

3. Incremental Form of Equation of Motion with Viscoelastic Material

Now if the viscoelastic damper is applied to the structural system, the resistance capacity of the system will be increased by a force $F=K_0x+K_1D^\alpha(x)$. This yields the Eq. (11)

$$M^*\ddot{x}(t)+C^*\dot{x}(t)+Kx(t)+F(t)=P(t), \tag{21}$$

where

$$M^*=M+\rho C_a V,$$

$$C^*=C+\rho C_d A\hat{u},$$

$$F(t)=K_0(t)+K_1D^\alpha(x(t)),$$

and the wave force $P(t)$ is obtained from Eq. (15) for regular harmonic waves or Eq.(20) for random waves. It is noteworthy that due to difficulties in determining the system damping, according to customary application, the system damping may be simplified by multiplying a damping factor ζ and corresponding natural frequency ϖ_n to the system mass as

$$C^*=2\omega_n\zeta M^*, \tag{22}$$

For derivation of the incremental equation, between time steps n and n+1, the equation with the incremental quantities can be rewritten as

$$M^*\Delta\ddot{x}_n+C^*\Delta\dot{x}_n+K\Delta x_n+\Delta F_n=\Delta P_n, \tag{23}$$

where the incremental quantities are

$$\Delta x_n=x_{n+1}-x_n;$$

$$\Delta\dot{x}_n=\dot{x}_{n+1}-\dot{x}_n;$$

$$\Delta\ddot{x}_n=\ddot{x}_{n+1}-\ddot{x}_n;$$

$$\Delta F_n=F_{n+1}-F_n,$$

and

$$\Delta P_n=P_{n+1}-P_n.$$

Based on Newmark's method (Newmark, 1962), assuming an average acceleration between two time steps n and n+1, and after integration, the increment of the velocity and acceleration becomes

$$\Delta\dot{x}_n=\frac{2}{\Delta t_n}\Delta x_n-2\dot{x}_n, \tag{24}$$

and

$$\Delta\ddot{x}_n=\frac{4}{\Delta t_n^2}(\Delta x_n-\dot{x}_n\Delta t)-2\ddot{x}_n, \tag{25}$$

where Δt_n is the increment of time between steps n and n+1. After substitution of $\Delta\dot{x}_n$ and $\Delta\ddot{x}$ back into Eq. (23), the incremental form may be written as follows:

$$K_n^*\Delta x_n=\Delta P_n^*, \tag{26}$$

where

$$K_n^*=K+[K_0+\frac{K_1\Delta t^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}]+\frac{4}{\Delta t_n^2}M^*+\frac{2}{\Delta t_n}C^*, \tag{27}$$

$$\Delta P_n^*=\Delta P_n-\Delta F_p+M^*[\frac{4}{\Delta t_n}\dot{x}_n+2\ddot{x}_n]+2C^*x_n, \tag{28}$$

and the previous effect of the force increment is

$$\Delta F_p=\frac{K_1\Delta t^{-\alpha}}{(1-\alpha)\Gamma(1-\alpha)}[\Delta W_0x(0)+\Delta W_nx(i\Delta t)], \tag{29}$$

where

$$\Delta W_0=W_0^{n+1}-W_0^n,$$

and

$$\Delta W_n=\sum_{i=1}^{n}W_i^{n+1}-\sum_{i=1}^{n-1}W_i^n.$$

Now by using Eq. (26), the displacement increment at time step n can be found easily. Substituting this displacement increment and the velocity and acceleration of the previous step back into Eqs. (24) and (25),

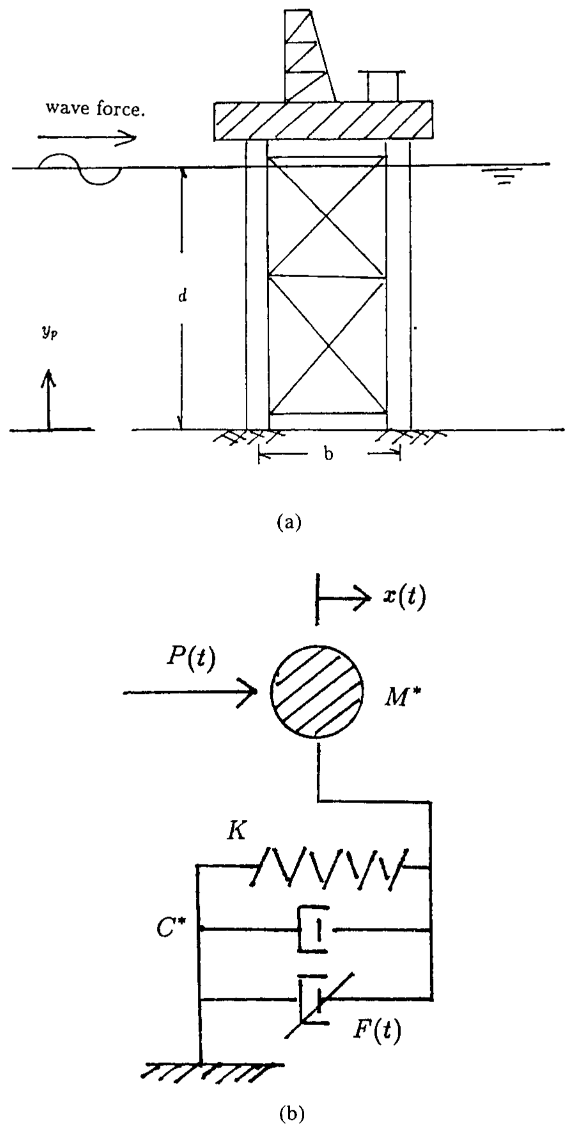


Fig. 2. Illustration of an offshore structure under numerical analysis. (a) Typical offshore structure. (b) Equivalent lumped mass model.

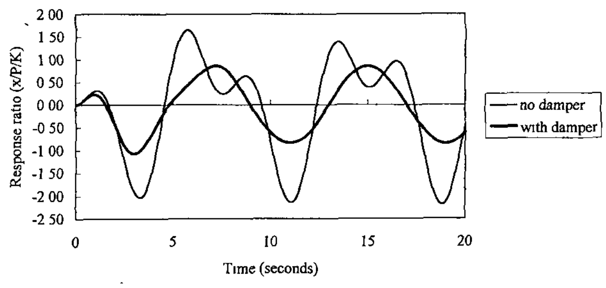


Fig. 3. Comparison of the displacement response ratio for regular wave force analysis.

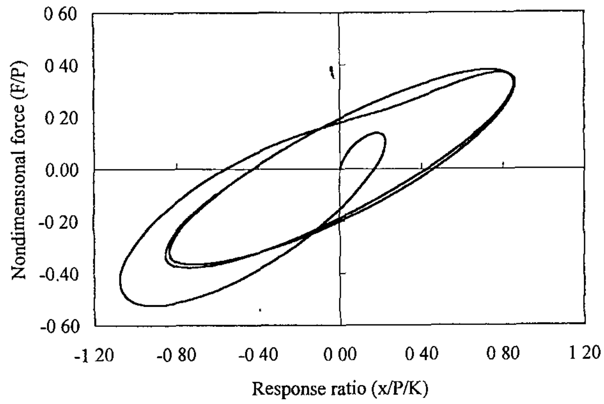


Fig. 4. Force-displacement curves of the damper in the regular wave analysis.

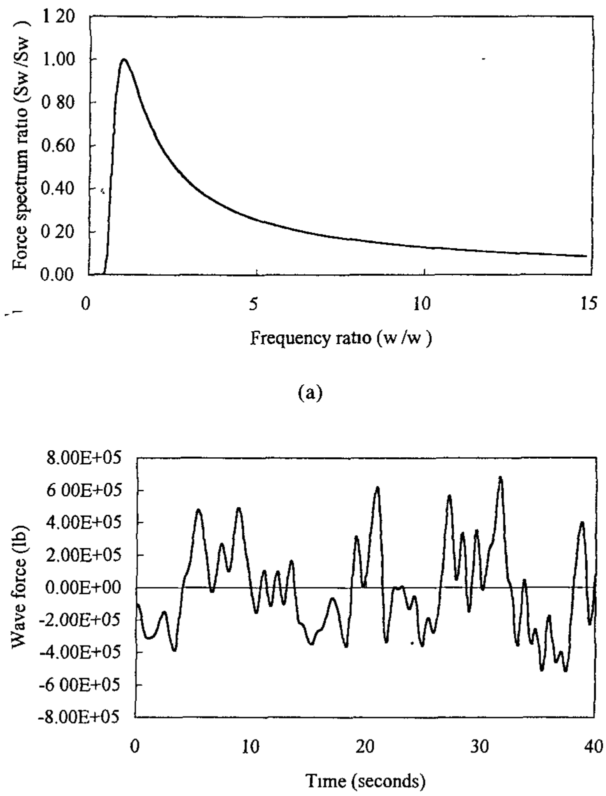


Fig. 5. (a) Force spectrum of random waves from the Pierson-Moskowitz wave spectrum. (b) Time history of random wave forces generated by the force spectrum.

the increment of the velocity and acceleration can be readily obtained.

IV. Numerical Results and Discussion

In the numerical analysis, a single degree of freedom system was assumed for a template platform located in a water of depth 250 ft as shown in Fig. 2(a), where the outer and the inner diameters of the vertical members were 4.0 ft and 3.75 ft, respectively. A simplified equivalent lumped mass system is also shown in Fig. 2(b), where the natural frequency is about 0.26 Hz for this system, corresponding to 5×10^6 lb/ft structural stiffness and 186.0×10^4 slugs mass assumed on the top platform. In this equivalent system, an additional damping force was provided by the viscoelastic material while the system damping characterized by the damping factor ζ was either taken into account or not. The viscoelastic dampers adopted in the analysis had typical empirical coefficients: $K_1=6\times10^4$ lb/ft, $B_0=1$, $\alpha=0.75$, $\beta=0.001$, $\beta_1=-0.089$, $\beta_2=0.0153$, $\beta_3=0.12$. Four categories of loading were input into the system, namely, the regular wave force based on small amplitude waves, the irregular random wave force based on the wave spectrum, the wave force with frequencies close to the structural system, and the step loading. The analysis was focused on the displacement induced by the input loading and the effect of displacement reduction when the viscoelastic dampers were applied.

In the first analysis, the wave force based on the small amplitude wave theory with 0.125 Hz frequency was applied. The properties related to the wave adopted in the analysis were: wave length l=300 ft, wave height H=20 ft, C_m=2, and C_d=2. Figure 3 represents the displacement response proportional to a displacement equivalent to P/K, the static response, when the system was subjected to wave forces, where significant reduction due to the additional damping on the response could be observed. Corresponding to this response, Figure 4 is the normalized force-displacement curve for the damper added into the structural system, where the area encompassed by the loops represents the dissipated energy.

When random waves were applied, a force spectrum obtained from the Pierson-Moskowitz wave spectrum was calculated and is shown in Fig. 5(a). Corresponding to this force spectrum, a time history

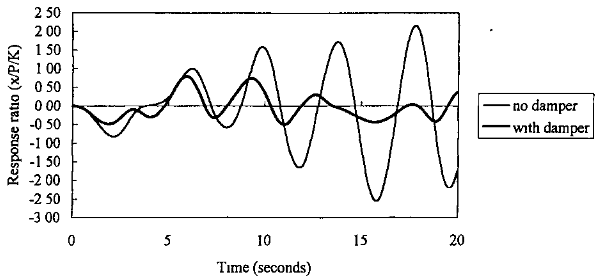


Fig. 6. Comparison of the displacement response ratios for the random wave analysis.

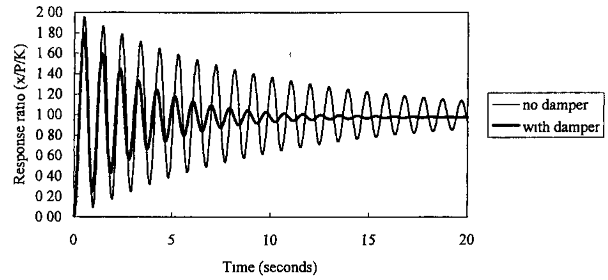


Fig. 8. Comparison of the displacement response ratios for the step loading analysis.

for the wave forces is also shown in Fig. 5(b), which was applied to the structural system in the random wave response analysis. When random forces were exerted on the structural system, the response ratio of the system was that presented in Fig. 6, in which again a reduction of the response amplitude is observed. Figure 7 shows the corresponding normalized force-displacement curves for the damper, in which a typical viscoelastic material behavior was again realized.

For the step loading and resonant force analysis, a stiffer structure was obtained as the structure was located in shallower water 120 ft deep, and the span of the platform was varied to 60 ft while the member dimensions and the mass on the top deck remained the same. The frequency of the structural system, thus, increased to 1.04 Hz. Figure 8 shows a comparison of the displacement response ratio for the system subjected to a step loading of which the magnitude is the same as the amplitude of the applied regular wave force. The system damping factor ζ was assumed to be 0.1 in the first curve when the damper was not applied whereas the system damping was assumed to be zero when the damper that provided the additional damping was applied. Both curves in the figure show decaying response motion, but the one with additional

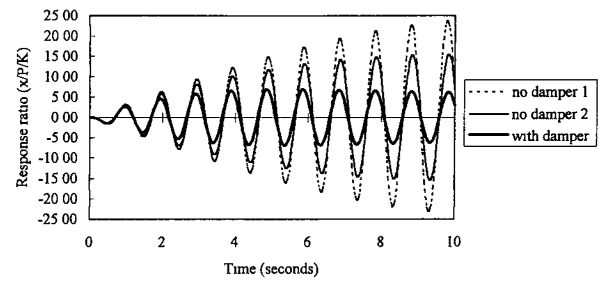


Fig. 9. Comparison of the displacement response ratios for the resonance analysis.

damping decays faster and also shows a slight increase in the frequency. Figure 9 shows a comparison of the response ratios when the system was subjected to a wave force with a frequency close to the system frequency, where the frequency ratio $r=f/f_n=0.95$, and the system damping factor ζ was assumed to be 0.0 for no-damper case 1 and with-damper case and 0.1 for no-damper case 2, respectively. A gradually amplified response was found for the structural system either with or without system damping, but when the additional damper was applied, the response retained nearly constant amplitude.

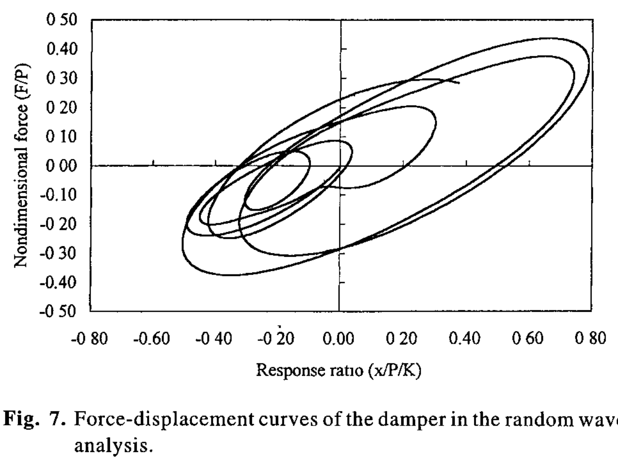


Fig. 7. Force-displacement curves of the damper in the random wave analysis.

V. Conclusions

As shown in the analysis, an incremental form of nonlinear analysis for the structural system combined with viscoelastic materials has been developed and successfully applied to the offshore structural system. From this preliminary study, it is concluded that a viscoelastic damper can be applied to an offshore structure, and that the vibration of the structure induced by either harmonic or random type wave forces can be reduced to a satisfactory level, such that the durability of the structure might be upgraded significantly. In most cases, the vibration of the structure can be reduced by 50%, and in extreme cases when resonance occurs in the system, the reduction of the vibration using the viscoelastic damper can reach a higher percentage. It is obvious that, when resonance occurs in a system, the vibration of the system will be governed by the system damping. Therefore, a device that can provide additional damping besides the system damping will be helpful in reducing the amplification phenomenon in the structural response. However, advanced analysis with closer examination of the local deformation behavior for a complete structural system subjected to a more complicated loading environment is recommended. It is also recommended that optimal design analysis be performed for various types of structural systems combined with most-fitting damping devices.

Acknowledgment

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Application of Damper in Offshore Structures

黏彈性阻尼於海洋結構之應用

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摘　要

本研究主要在探討黏彈性阻尼解析模式的發展，及其應用於海洋結構時之減振效應。在結構上由風力及地震力所產生的劇烈振動，常導致結構的變形及破壞。爲了改善這種情形，具有高度吸能能力的黏彈性阻尼，乃被應用於結構中，來加強結構體的動力性能。而海洋結構、除了風力之外、由波浪及流所產生的振動，更將加重結構的變形及破壞。因此，如果能將具有良好吸能能力的黏彈性阻尼應用於海洋結構中，對於結構的動力性能將有良好改善。

本文中分析一簡化的海洋結構系統，受到規則波或隨機波浪所產生外力，分別作用時的動力行爲。其中，波力引用Morrison的方程式作用於細小物體，波浪則假設爲微小振幅波。針對此非線性系統在時間域的反應分析，本文中導出了一包含了黏彈性阻尼解析模式的增量運動方程式。由分析的結果中發現，加了黏彈性阻尼後，海洋結構物受到動力作用時所產生的振動，有明顯的降低效果。