Dynamic analysis of 1100 kV composite bushing considering oil and structure interaction effects

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Abstract. The 1100 kV composite bushing is one of the most important components in the ultra-high voltage electrical network. Therefore, the safety and integrity must be ensured during the operation under any conditions such as an earthquake. The primary object of this paper is to investigate the effects of oil in the dome on the dynamic responses of the 1100 kV composite bushing when subjected to horizontal seismic ground motion. The coupled finite element method (FEM) and smoothed particle hydrodynamics (SPH) method is adopted to simulate the fluid structure interaction (FSI) between the oil and the dome. The influences of particle's distributions on the numerical results and computational efficiencies are discussed. For comparison with the coupled FEM/SPH method, the additional mass model is also performed. The influences of oil oscillation on the time history of absolute acceleration of 1100 kV composite bushing are discussed, as well as the relative displacement and the bending moment at the base of the structure. The results show that the motion of oil in the dome with free surface can limit the vibration of the 1100 kV composite bushing and can efficiently dissipate the kinetic energy of the 1100 kV composite bushing by fluid-structure interaction.

1 Introduction

As an important component of the electrical substation, the composite bushing that connects the transformer and the cable has suffered serious damage in previous earthquakes [1, 2]. In order to accurately describe the dynamic behavior of the bushing, many experiments and numerical analyses have been done.

The shake table tests [3, 4] were performed to investigate the influences of the transformer's top plate on the bushing's response by a new support structure with rigid frame and flexible top plate. Moreover, the numerical method was also adopted to investigate the influence of the flexibility of transformer plate and the installed location on the amplification factor [5, 6]. In these numerical models, the bushings were generally simplified as beam elements with approximate geometries for seismic analyses. Only barely

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few work was conducted to simulate the bushing in detail [7, 8]. However, this method separately calculates the dynamic responses of the oil and the transformer-bushing system without oil, which can't accurately capture the FSI phenomena and is different to implement in seismic analysis.

Considering the structural characteristics of the composite busing, the oil in the dome with free surface may produce violent free-surface flows under large external excitations. Numerical simulation of the liquid sloshing in the dome is very difficult for the traditional grid-based methods, as it involves breaking waves, strong turbulence and vortex. Smoothed particle hydrodynamics (SPH) as a fully meshfree Lagrangian particle method has significant advantages to predict the free-surface flows. [9-12] SPH was found to provide an accurate prediction of liquid sloshing and had been successfully applied to simulate engineering problems involving large deformations, such as the liquid sloshing in stabilizer tank of ship [13, 14] and the liquid flow in the nuclear power [15, 16]. It can be seen that the coupled finite element method (FEM) and SPH method provides sufficient accuracy and efficiency for simulations of practical engineering with FSI problems.

In this paper, the effects of oil in the dome on the dynamic responses of the 1100 kV composite bushing subjected to horizontal ground motion are studied. Based on the advantage of SPH method in simulating the liquid sloshing with free surface, the coupled FEM/SPH method is adopted to simulate the FSI problems. A dynamic analysis is performed for the 1100 kV composite bushing.

2 Methods and numerical model

2.1 Basic equations of SPH method

The SPH as a mesh-free Lagrangian method is suitable for modelling liquid sloshing with large deformations. In this method, the liquid domain is represented by a set of particles with individual mass, density and pressure. The particles are moved by the governing equations. The particles interact with each other in a finite support domain defined by the smooth function. A detailed description of SPH method and the governing equations used in this paper can be found in literatures [9-11, 15] and hence only the main equations are presented herein. A filed function $f\left(x_i\right)$ and its derivative at the position of ith-particle can be written in the following forms [9]:

$$\left\langle f\left(x_i\right)\right\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f\left(x_j\right) W\left(x_i - x_j, h\right) \tag{1}$$

$$\left\langle \nabla \cdot f\left(x_i\right)\right\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f\left(x_j\right) \nabla_i W_{ij} \tag{2}$$

where m_j and ρ_j are the jth-particle mass and density, respectively. x_i and x_j are the positions of corresponding particles. N is the number of particles in the support domain. W is the smooth function or kernel function and h is the smooth length of the kernel. In this paper, the cubic B-spline function is used as the smooth function

$$W\left(R,h\right) = \frac{3}{2}\pi h^3 \times \begin{cases} 2/3 - R^2 + 1/2R^3, & 0 \le R < 1 \\ 1/6\left(2 - R^3\right), & 1 \le R < 2 \\ 0, & R \ge 2 \end{cases} \tag{3}$$

where R is the relative distance between two particles, $R = \left| x_i - x_j \right| / h$. The SPH equations of motion for the governing Navier-Stokes equations can be written as

$$\begin{cases} \dfrac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j v_{ij}^{\beta} \dfrac{\partial W_{ij}}{\partial x_i^{\beta}}, \\ \dfrac{Dv_i^{\alpha}}{Dt} = -\sum_{j=1}^{N} m_j \left(\dfrac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \dfrac{\sigma_j^{\alpha\beta}}{\rho_j^2} + \Pi_{ij} \right) \dfrac{\partial W_{ij}}{\partial x_i^{\beta}} + F_i, \\ \dfrac{De_i}{Dt} = \dfrac{1}{2} \sum_{j=1}^{N} m_j \left(\dfrac{p_i}{\rho_i^2} + \dfrac{p_j}{\rho_j^2} \right) v_{ij}^{\beta} \dfrac{\partial W_{ij}}{\partial x_i^{\beta}} + \dfrac{\mu_i}{2\rho_i} \varepsilon_i^{\alpha\beta} \varepsilon_i^{\alpha\beta}, \end{cases} \tag{4}$$

where α and β denote the coordinate directions; $v, e, \sigma, \varepsilon, F, p, \mu$ are the velocity, the internal energy, the stress, the shear strain rate, the external force, the pressure and the dynamic viscosity, respectively. Π_{ij} is the artificial viscosity, which can be obtained from the literature [11].

2.2 Numerical model of 1100 kV composite bushing by FEM/SPH method

The longitudinal section of the 1100 kV composite bushing is shown in Figure 1(a). The bushing is axisymmetric. The flange plate that belted to the transformer tank is used to fix the bushing to the transformer. The composite unit and the metallic dome are above the flange plate, while the lower support and the porcelain insulator are below. In cross section, the bushing is organized with a copper core, a multi-layered kraft paper, a composite unit and transformer oil filled in the gap. The shed covering the composite unit provides a hydrophobic layer. Figure 1(b) presents the simplified three-dimensional EFM/SPH model. In this model, the composite unit is simulated by BEAM188 with appreciate geometry, stiffness and mass. It is feasible because the oil is full up to its top all the time and the sloshing characteristics can be neglected. The oil in the metallic dome will conduct free-surface flows with large deformations. From this point, the oil in this domain is simulated by SPH particles. The contact algorithms [15] are adopted for the coupled FEM/SPH method. The dimensions of the dome and the distributions of the SPH particles are shown in Figure 1(c) and Figure 1 (d).

In SPH model, the pressure of oil is calculated by the following Gruneisen equation of state [15]:

$$p = \frac{\rho_0 B^2 \mu \left[1 + \left(1 - \dfrac{\gamma_0}{2} \right) \mu - \dfrac{a}{2} \mu^2 \right]}{\left[1 - \left(S_1 - 1 \right) \mu - S_2 \dfrac{\mu^2}{1 + \mu} - S_3 \dfrac{\mu^3}{\left(1 + \mu^2 \right)} \right]^2} + \left(\gamma_0 + a\mu \right) E \tag{5}$$

where $\rho_0, B, \gamma_0, a, E$ represent the initial density, the intercept of v_s-v_p curve, the Gruneisen gamma, the first order volume correction to γ_0 and the initial energy; S_1, S_2 and S_3 are the coefficients of the slope of v_s-v_p curve and $\mu = \rho / \rho_0 - 1$. The material properties of the FEM/SPH model are listed in Table 1.

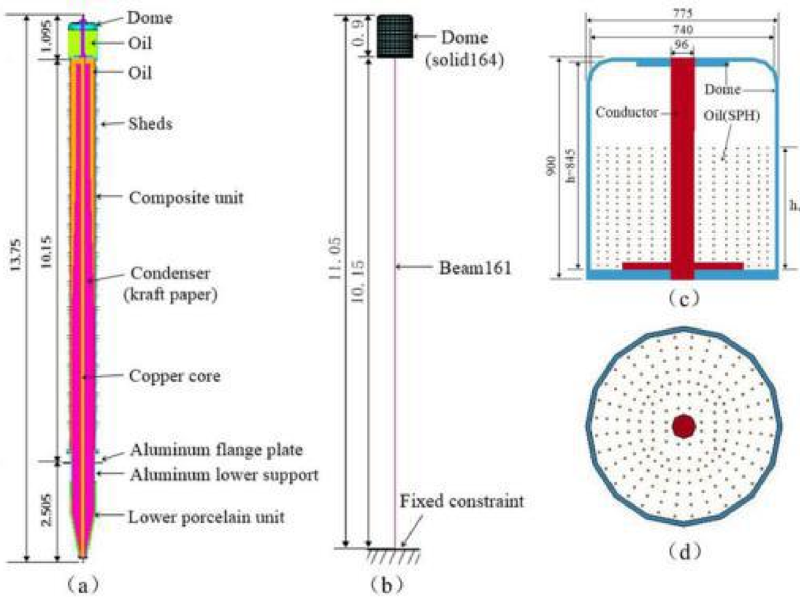

Fig. 1. Sketch of the 1100kV composite bushing (a) longitudinal section (m); (b) simplified model (m); (c) geometry of the metallic dome (mm); (d) distribution of SPH.

Table 1. Materials for 1100kV composite bushing.

Material		Equivalent BEAM elements		Dome	Conductor	Oil
Density (kg/m^3)		1460		2680	8500	895
Young's modulus (GPa)		1.6		70	100	1.8
Poisson's ratio		0.2		0.2	0.2	
Viscosity coefficients (N·s/m^2)						0.01
Main parameters of Gruneisen for oil						
B	S_1	S_2	S_3	γ_0	a	E
1418	2.56	1.99	1.23	0.5	0	0

The Rayleigh damping is applied in the FEM model. The damping matrix $[C]$ is the linear combination of mass and stiffness matrixes:

$$[C]=\alpha[M]+\beta[K] \tag{6}$$

where $[C]$, $[M]$ and $[K]$ are the damping, mass and stiffness matrixes, respectively.

2.3 Dynamic analysis

The dynamic analysis of the 1100 kV composite bushing is performed by the FEM/SPH method. The bushing without oil in the dome is simulated by FEM, while the oil in the dome is simulated by SPH particles. The recorded seismic ground acceleration in horizontal direction is shown in Figure 2. The peak ground acceleration is 0.4g. In this figure, however, the amplification factor of 2 due to the transformer body is considered, which is recommended by IEEE 693 standard.

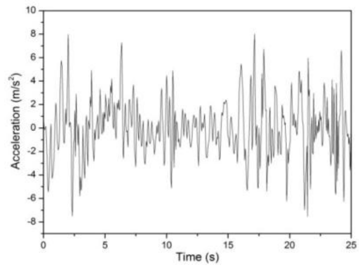

Fig. 2. Recorded seismic ground motion.

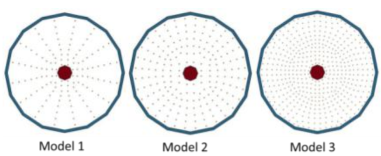

Fig. 3. Distributions of particles in the dome.

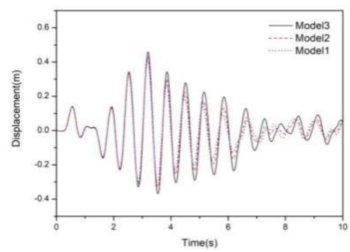

Fig. 4. Top displacements of bushing relative to ground with different models.

2.3.1 Analysis of the distribution of SPH particles.

It is well known that the more particles with well-distributed, the more accurate prediction of liquid motion, but will produce greater computer memory space. Therefore, it is necessary to find out the acceptable distribution of particles due to limitations of the computer and software.

The numerical model with half-full oil in the dome is adopted. The distributions of particles in the dome are presented in Figure 3. The 0～10 s of the recorded ground motions (as shown in Figure 2) are selected as the excitation loads. The time histories of the top displacement relative to the ground with different models are shown in Figure 4. The peak of the relative displacement and the computational time with different models are listed in Table 2. It can be seen that the error of peak displacement between model 1 and model 3 is 9.8%. And that between model 2 and model 3 is 5.9%. This means the calculated results converge with the increase of the particles. Thus it can simulate the liquid flow more accurately. However, more particles will induce larger computational time as shown in Table 2. The least computational time is achieved in model 2 due to its well-distribute particles. Considering the accuracy and the computational efficiency, model 2 is adopted in the following dynamic analysis.

Table 2. Peak relative displacements and computational time with different models.

Models	Model 1	Model 2	Model 3
Peak Relative displacements (mm)	413.50	430.96	458.19
Numbers of particles	3084	4604	11256
Computational time (minute)	555	485	2072

2.3.2 The time history analysis.

The 1100 kV composite bushing with half-full oil in the dome is performed by FEM/SPH method. The distribution of particles in model 2 is adopted during the analysis. For comparison, another numerical model that treats the oil in the dome as additional masses is also conducted. In this model, the additional masses are added to the dome. The excitation loads are shown in Figure 2. The seismic ground accelerations are applied to the structure as inertia forces. In order to accurately simulate the liquid sloshing problems, the gravity in vertical direction is also considered.

3 Results and discussions

This study investigates the influence of oil sloshing with free surface on the dynamic responses of the 1100 kV composite bushing. The oil in the dome is simulated by SPH particles and additional masses separately. Figure 5 describes the time histories of absolute acceleration at the top of the 1100 kV composite bushing. It can be seen that the oil simulated by SPH agree well with that by additional masses at the beginning. It is because the oil sloshing characteristics modeled by SPH have not been excited at the beginning of excitation. A few minutes later, the amplitudes of the absolute acceleration simulated by SPH are obvious lower than that simulated by additional masses. This phenomenon can also be seen in [17].The maximum absolute accelerations of the SPH method and the additional mass method are 44.91 m/s^2 and 52.16 m/s^2, respectively. The reduction ratio of absolute acceleration is 13.9% due to the liquid sloshing characteristics. Figure 6 presents the top displacement relative to the ground with different oil-simulated methods. The maximum peak displacements are 373.7 mm and 446.5 mm, when the oil is simulated by SPH particles and additional masses separately. The maximum reduction ratio reaches to 16.3%.

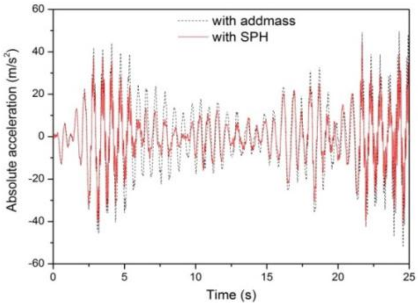

Fig. 5. Time histories of absolute acceleration at the top of the composite bushing.

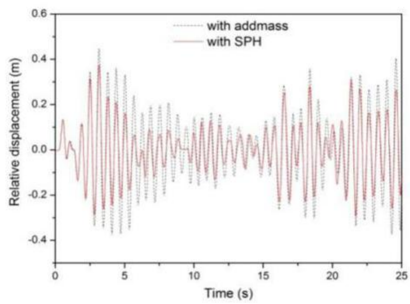

Fig. 6. Time histories of top displacement relative to the ground.

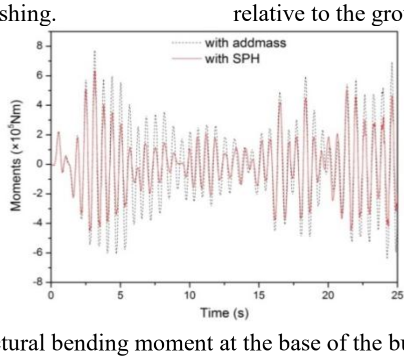

Fig. 7. Time histories of structural bending moment at the base of the bushing.

In addition, the majority of the bushing stress during seismic loads occurs due to bending. From this viewpoint, the peak bending moment at the base of the bushing is also selected as an evaluating parameter. The bending moment time-history curves of the 1100 kV composite bushing are shown in Figure 7. As can be seen from this figure, the maximum bending moment is 6.35 N·m in the coupled FEM/SPH model, while that is 7.73 N·m when the oil is modeled by additional masses. The corresponding reduction ratio is 17.8%.

4 Conclusions

This paper performed the dynamic analysis of the 1100 kV composite bushing using FEM/SPH method to simulate the FSI between the oil and the dome. First of all, the distributions of the SPH particles in the dome are discussed. It confirms that the more particles with uniform distribution will produce more accurate results. Considering its accuracy and efficiency, the Model 2 with rather accurate results and more efficient computational time are adopted. And then, the dynamic analysis of the 1100 kV composite bushing with well-distributed particles is conducted under the horizontal ground motion. It is obvious that the coupled FEM/SPH method can accurately describe the FSI between the oil and the dome. Comparing with the traditional simplified approach that the oil is added to the dome with additional masses, the oil sloshing with free surface in the dome will significantly reduce the dynamic responses of the composite bushing, such as the absolute acceleration, the relative displacement and the bending moment at the base of the bushing.

Indeed, only one recorded ground motion is considered in this paper. The influence of FSI on The structural dynamic responses is also relevant to the input ground motions. Thus more studies should be done in the future.

References

1. Mosalam K M,Günay S 2014 *Earthquake Strut D.* **43** 1205-22
2. Sun Y H, Liu W Y, Su Z G and Liu Z L 2014 *Advanced Materials Research* **1065-1069** 1480-4
3. Kong D 2010 *Evaluation and protection of high voltage electrical equipment against severe shock and vibrations* State University of New York at Buffalo
4. Gilani A S, Whittaker A S,Fenves G L 2011 *Earthqauake Spectra* **4** 597-616
5. Fahad M 2013 *Seismic evaluation and qualification of transformer bushings* State University of New York at Buffalo p 373
6. Ersoy S, Saadeghvaziri M A 2004 *IEEE T Power Delliver.* **19** 131-7
7. Okuno M, Setoyama T, Murase S and Hellested R. 1990 *IEEE T Power Deliver* **5** 955-60
8. Platek R, Sekula R, Lewandowski B 2010 *IEEE T Dielect El In* **17** 408-16
9. Shao J R, Li H Q, Liu G R and Liu M B 2012 *Comput Struct* **100-101** 18-26
10. Chen Z, Zong Z, Li H T and Li J 2013 Ocean Eng 59 129-41
11. Marsh A, Prakash M, Semercigil E and Turan O F 2011 J Fluid Struct 27 1165-81
12. Marsh A P, Prakash M, Semercigil S E and Turan O F 2011 J Sound Vib 330 6287-95
13. Souto Iglesias A, Pérez Rojas L, Zamora Rodríguez R 2004 Ocean Eng 31 1169-92
14. Cao X Y, Ming F R,Zhang A M 2014 Appl Ocean Res 47 241-54
15. Xu Q, Chen J, Zhang C, Li J and Zhao C 2016 Nucl Eng Technol 48 246-58
16. Vorobyev A, Kriventsev V, Maschek W 2011 Nucl Eng Des 241 3086-96
17. Roy A, Ghosh A D, Chatterjee S 2017 Structural Control and Health Monitoring 24 e1924