Effect of Coulomb Friction on Dynamic Response of Reactor Pressure Vessel System Under Extreme Loadings

D. R. Bhandari
Westinghouse Electric Corporation, Pittsburgh, PA USA
C. B. Gilmore
Westinghouse Electric Corporation, Columbia, SC USA

ABSTRACT

In the dynamic analysis of nuclear power plants, it may be necessary to include sliding and lift-off in the mathematical model of the nuclear supply system. This is due to the fact that various equipment and components are generally not fastened to adjacent structural members or to the supporting foundation and, therefore, may slide or lift-off when subjected to extreme loads. This paper presents a nonlinear transient dynamic time history analysis of a Pressurized Water Reactor (PWR) vessel and its internals subjected to seismic loads.

Non-linearities in the pressure vessel system are due to gaps between adjacent components, friction sliding between various interfaces and potential lift-off the components from their supports. The transient analysis includes impacting due to gap closures, energy losses due to impacting bodies and Coulomb friction between sliding surfaces. The results of these nonlinear analyses show that the incorporation of Coulomb friction in the mathematical model can significantly reduce the dynamic response of the system when subjected to external loads, and thereby increase predicted design margins of the component.

INTRODUCTION

Most equipment and components in nuclear power plants are not structurally fastened to adjacent members or to the supporting foundation and, therefore, may slide when subjected to external forces. Furthermore, these equipment and components are required to be designed to withstand extreme loads resulting from events such as earthquake and/or loss-of-coolant-accident (LOCA). In the dynamic analysis of these components, it may be necessary to model sliding and lift-off between the components and adjacent structures or supporting foundation. The nuclear power plant components for which sliding and lift-off may be of importance are the reactor internals. A major function of the reactor internals, located within the reactor pressure vessel, is to maintain the reactor core in a coolable geometry following a seismic or LOCA event. As a result of these sudden external forces, the reactor internals tend to slide relative to the reactor pressure vessel and may simultaneously lift-off the reactor vessel flange. Another instance of such components where the sliding phenomenon may be of importance is the fuel racks which store spent fuel assemblies in a water-filled pool. Normally, the fuel racks are fastened to the floor of the pool; however, some applications do not permit the racks to be fastened to the floor. The unsecured fuel racks standing freely on the floor may slide, tip or lift-off-during a seismic event.

In a mathematical representation of the reactor pressure vessel and its internals the sliding phenomenon can be modeled using a three-dimensional dynamic friction element. This element simulates the interaction between contacting bodies which slide and separate as a result of dynamic excitation. The main advantage of including the friction element in the mathematical model of a structural system is the ability to model the energy dissipation, or hysteresis, at the structural interface. In addition to providing a more realistic assessment of impacting loads at the friction interface, inclusion of the hysteresis effect may also change the system response significantly ("de-tune") when compared to results which neglect Coulomb friction.

Most solution procedures for transient dynamic analysis can be divided into two categories: a) direct integration method; and b) modal superposition method. For design purposes, seismic excitations are generally of 10 to 20 seconds duration. Application of direct integration method to large nonlinear dynamic problems typical of nuclear power plants under seismic excitations becomes prohibitive because of excessive computational resources, or cost. Therefore, to reduce the computational cost of such nonlinear problems, the application of modal superposition method (Molnar 1976, Shah, et al., 1979) is considered.

In this paper, three-dimensional friction elements are used to study the effects of Coulomb friction on the dynamic response of the reactor pressure vessel and its internals. Mathematical formulation for the solution of the nonlinear dynamic problems using modal superposition technique is given in Section 2. A brief discussion on the finite element representation of a typical nuclear reactor vessel and its internals is given in Section 3. Also given in Section 3 is the description of a three-dimensional friction element simulating the sliding and lift-off phenomena between various contacting surfaces. Finally, the effects of Coulomb friction on the dynamic response of the reactor pressure vessel system, including the core, are presented in Section 4.

MATHEMATICAL PRELIMINARIES

The generalized equation of motion of a structure is given by:

$$[M]\,\{\ddot{X}\} + [C]\,\{\dot{X}\} + [K]\,\{X\} = \{F\} \qquad (2\text{-}1)$$

where [M], [C] and [K] denote mass, damping and stiffness matrices, respectively. The displacement, velocity, acceleration, and the applied force vectors are represented by $\{X\}$, $\{\dot{X}\}$, $\{\ddot{X}\}$ and $\{F\}$, respectively. The dependence of $\{F\}$ on the spatial coordinates and time is understood.

The damping and stiffness matrices in (2-1) are nonlinear in terms of displacement vector $\{X\}$ and are decomposed into linear and nonlinear parts:

$$[C] = [C_l] + [C_{nl}] \qquad (2\text{-}2a)$$

$$[K] = [K_l] + [K_{nl}] \qquad (2\text{-}2b)$$

Here $[C_l]$ and $[K_l]$ are damping and stiffness matrices representing the reference state of the structure; $[C_{nl}]$ and $[K_{nl}]$ are the nonlinear parts dependent on velocity and displacement. Substitution of (2-2a) and (2-2b) into (2-1) yields:

$$[M]\,\{\ddot{X}\} + [C_l]\,\{\dot{X}\} + [K_l]\,\{X\} = \{F\} - \{F_{nl}\} \qquad (2\text{-}3)$$

where the pseudo force vector is defined by:

$$\{F_{nl}\} = [C_{nl}]\,\{\dot{X}\} + [K_{nl}]\,\{X\} \tag{2-4}$$

Equation (2-3) is solved by the use of modal decomposition whose modes are solution of (2-3) with vanishing righthand side. The homogeneous, undamped equation of motion representing the reference state of the structure is:

$$[M]\,\{\ddot{X}\} + [K]\,\{X\} = \{0\} \tag{2-5}$$

Let $[\Omega]$ and $[\Phi]$ denote the natural frequency and normalized mode shape matrices associated with (2-5). Then with the aid of transformation:

$$\{X\} = [\Phi]\,\{q\} \tag{2-6}$$

and the orthogonality relations

$$\begin{aligned} &[\Phi]^T\,[M]\,[\Phi] = [I] \\ &[\Phi]^T\,[K_l]\,[\Phi] = [\Omega_j^2] \\ &[\Phi]^T\,[C_l]\,[\Phi] = [2\Omega_j\,\zeta_j] \end{aligned} \tag{2-7}$$

the resulting modal equations become:

$$\{\ddot{q}\} + [2\,\Omega_j\,\zeta_j\}\,\{\dot{q}\} + [\Omega^2{}_j]\,\{q\} = \{Q\} - \{Q_{nl}\} \tag{2-8}$$

where,

ζ_j = percent of critical damping for the jth mode

$\{Q\}$ = $[\Phi]^T\,\{F\}$, the generalized applied force vector

$\{Q_{nl}\}$ = $[\Phi]^T\,\{F_{nl}\}$, the generalized pseudo force vector

Arrays $\{q\}$, $\{\dot{q}\}$, and $\{\ddot{q}\}$ are the modal displacements, velocity and acceleration, respectively. The generalized pseudo force vector is a function of displacement and velocity. Equation (2-8) represents a set of uncoupled equations. These equations are integrated analytically to eliminate numerical damping or frequency distortions during integration and the integration scheme is described in (Molnar 1976, Shah et al., 1979).

FINITE ELEMENT REPRESENTATION OF REACTOR VESSEL SYSTEM

A typical pressurized water reactor vessel and its internals are shown in Figure 1. The reactor internal components can be characterized by two major assemblies consisting of upper internals assembly and lower internals assembly. The main purposes of these assemblies are to channel flow, provide support and restraint to the core (fuel assemblies). The upper internals assembly consist of upper support assembly, guide tubes, support columns, and upper core plate. The upper support assembly transfers the dynamic loading of the upper internals assembly in the vessel. The lower internals assembly consisting of the lower support plate, lower core plate and the core barrel provide support to the core and transfer loads to the vessel through the core barrel flange. The components which are likely to experience sliding and lift-off due to dynamic excitations are, therefore, located at the mating surfaces of the vessel, core barrel and upper support flanges. These interface surfaces are highlighted in Figure 1. Three-dimensional dynamic friction elements are incorporated at these surfaces to simulate the sliding phenomena.

The mathematical representation of the reactor pressure vessel (RPV) system shown in Figure 2 is a three-dimensional non-linear finite element model. This model, which is developed using (WECAN 1988) Computer code, is best described as three concentric submodels consisting of a combination of nonlinear impact and linear elements. The outermost submodel represents the reactor vessel and its support structure. The second submodel represents the reactor core barrel assembly and is located inside the reactor vessel model. The third, or innermost, submodel represents the upper and lower support plates, upper and lower core plates, and fuel assemblies. Horizontal impact between the submodels is simulated using concentric nonlinear gap elements. The finite element library used in the model of Figure 2 consists of:

- Three-dimensional elastic pipe
- Three-dimensional mass with rotary inertia
- Three-dimensional beam
- Three-dimensional linear spring
- Concentric impact element
- Colinear impact element
- 6 x 6 stiffness matrix
- 12 x 12 stiffness matrix
- 12 x 12 mass matrix
- Two-dimensional rotary spring
- Three-dimensional friction element

COULOMB FRICTION REPRESENTATION

Coulomb friction is used to represent the energy dissipation resulting from sliding between contacting surfaces. The external force acting on the contact surfaces has two components: one acting normal to the contact surfaces and the other acting in the plane of contact. The latter component is referred to as shear force. A friction force exists between the contact surfaces and acts in a direction opposing the shear force. As the magnitude of the shear force increases, the magnitude of the friction force increases until its magnitude becomes equal to the product of the normal force (P_n) and a static coefficient of friction (μ_s). Sliding between two contact surfaces takes place when the shear force (F_s) becomes greater than the static friction force, i.e.,

$$F_s > \mu_s P_n \qquad (3\text{-}1)$$

During sliding, the friction force is equal to the product of the normal force and the dynamic coefficient of friction (μ_d).

This ideal friction behavior is illustrated in Figure 3a and is approximated by the friction element of Figure 3b. Note that in Figure 3b, nodes I & J are located on each contact surface. Node K is fixed in space. The direction K_I is along the direction of sliding. The friction spring (K_f) between nodes K and I simulates the friction behavior between two contact surfaces. The damper (C_I), spring (K_I) and the parameter GAP between two nodes I and J simulate the possibility of separation of and impact between two contact surfaces. At the initiation of sliding, the relative displacement between two surfaces in the direction of sliding is nonzero and is equal to $\mu_s P_N/K_f$. As the stiffness of the friction spring increases, the magnitude of the relative displacement decreases, and the behavior simulated by the friction element will be closer to the ideal behavior. The magnitude of K_f is selected such that the relative displacement $\mu_s P_N/K_f$ is a small fraction of the total displacement due to sliding.

Verification

The modal superposition method in the WECAN Computer Code has been verified extensively. In (Molnar 1976 and Shah et al., 1979) numerous problems were solved to verify nonlinear dynamic capability involving impact between structural components. Later, the scope of this method was expanded (Shah et al., 1983) to include the nonlinearity due to Coulomb damping (friction). Numerous verification problems have been solved (Gilmore 1985) to verify the two and three-dimensional capability of the Coulomb friction element.

DYNAMIC RESPONSE OF REACTOR PRESSURE VESSEL SYSTEM WITH COULOMB FRICTION

The effect of Coulomb friction on transient dynamic response of the reactor pressure vessel and its internals is presented in this section. As mentioned earlier, the solution of a system of nonlinear equations is obtained through modal superposition technique. Time history seismic excitations (accelerations) were applied to the finite element model of Figure 2 to obtain the dynamic response of the system. For the purpose of illustration, two cases were considered; one without the Coulomb friction, i.e., $\mu_d = 0.0$ and the other with $\mu_d = 0.15$.

Figure 4a shows the time history relative displacements of the reactor vessel flange and the core barrel flange (Figure 2; nodes 2 and 5) without Coulomb friction, while Figure 4b shows the relative displacements of the same nodes with $\mu_d = 0.15$. A comparison of relative displacements with and without friction for the reactor vessel and the core barrel nozzle (i.e., nodes 3 and 12) is shown in Figure 5. Finally, the impact forces between nodes 3 and 12 with and without friction are presented in Figure 6.

The above results show that the inclusion of Coulomb friction in the mathematical model can significantly reduce the dynamic response, thereby increasing the calculated design margins of safety of the components. For certain components such as the fuel assemblies, it may be desirable to demonstrate improved design margins of safety. This aspect becomes more important, especially for the high seismicity regions. Figure 7 shows the fuel assembly/core barrel impact loads with and without friction. Even though the fuel assemblies are physically located far away from sliding interface, there is significant reduction in the dynamic response of fuel assemblies when Coulomb friction is included in the system response. Furthermore, frequency analysis of the transient response in figure 4 shows a reduction in the fundamental frequency of the displacement response when Coulomb friction is included in the solution.

Similar dynamic analyses have been performed for LOCA excitations and the results of LOCA analyses also show a significant change in the system response when Coulomb friction is included in the system model.

CONCLUSIONS

a. The design margins of safety can be increased by including energy losses due to friction in the mathematical model of the system.

b. A more realistic assessment of frequency content of the transient response can be achieved by including Coulomb friction in the mathematical model.

c. Modal superposition method may be used to analyze a structure which have nonlinearities due to gap closures and Coulomb friction between sliding surfaces.

d. Significant reduction in computer cost can be achieved by using modal superposition with Coulomb friction.

REFERENCES

Gilmore, C. B., (1985) "Transient Dynamic Analysis of a Platform with Coulomb Damping (Friction) Supports," Ninth WECAN/FIGURES Users' Colloquim, Westinghouse R&D Center, Pittsburgh, Pa.

Molnar, A. J., Vashi, K. M., and Gay, C. W., (1976) "Application of Normal Mode Theory and Pseudoforce Methods to Solve Problems with Nonlinearities," ASME Journal of Pressure Vessel Technology, pp. 151-156.

Shah, V. N., Bohm, G. J., and Nahavandi, A. N., (1979) "Modal Superposition Method for Computationally Economically Nonlinear Structural Analysis," ASME Journal of Pressure Vessel Technology, Vol. 101, pp. 134-141.

Shah, V. N., and Gilmore, C. B., (1983) "Seismic Analysis of Structures with Coulomb Friction," Journal of Pressure Vessel Technology, Vol. 105, pp. 171-178.

WECAN (1988) Users' Manual, ed. A. W. Filstrup, Westinghouse Research Laboratories, Pittsburgh, Pa.

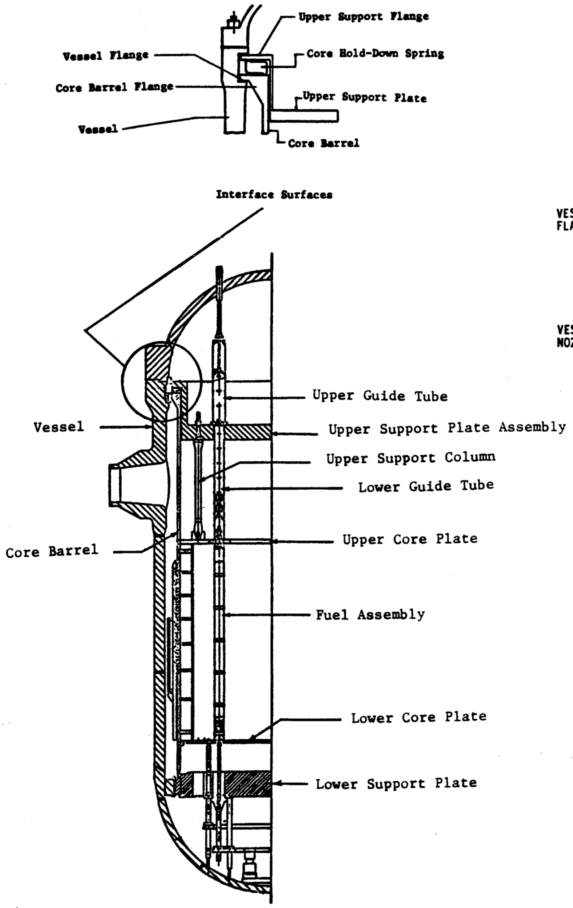


Figure 1 Reactor Vessel and Internal Components

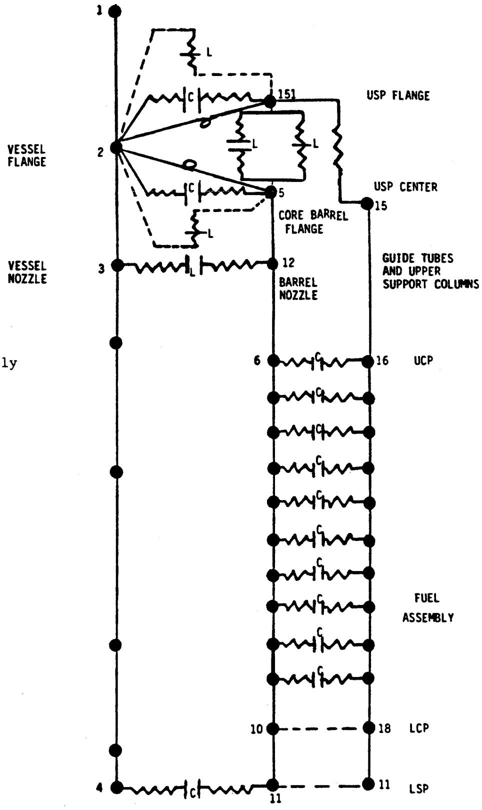


Figure 2 Finite Element Representation of Reactor Pressure Vessel System

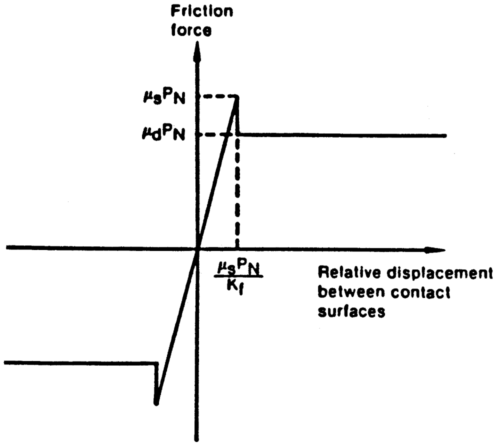


Figure 3a. Idealized Friction Behavior

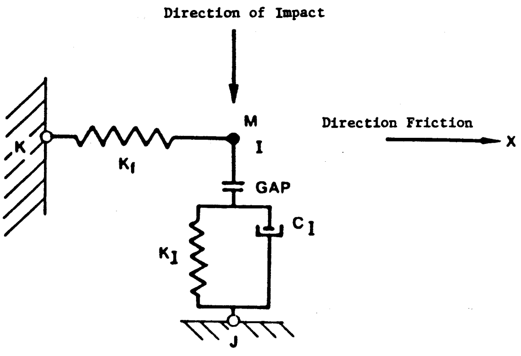
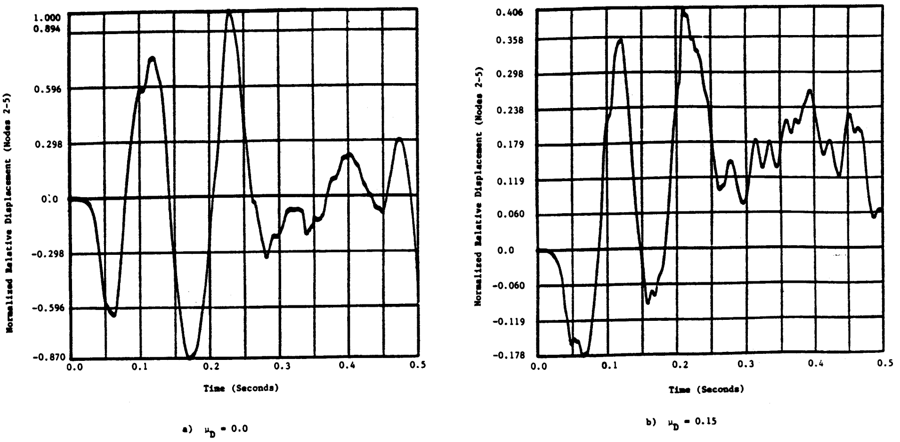


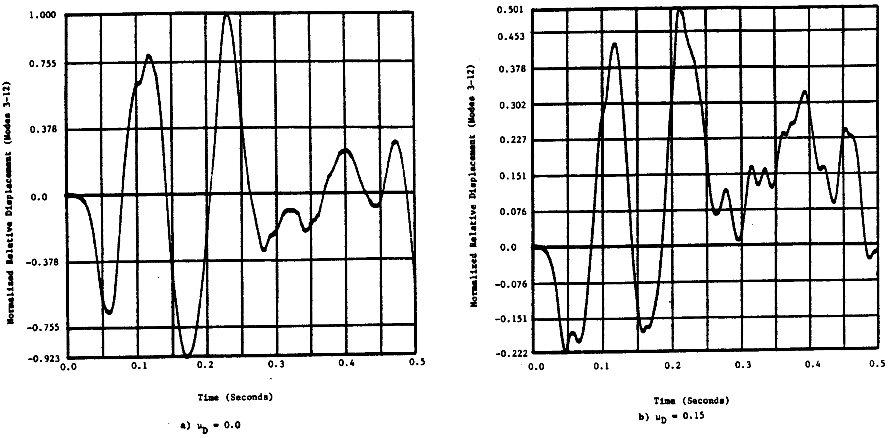
Figure 3b. 3-D Dynamic Friction Element



a) $\mu_D = 0.0$

b) $\mu_D = 0.15$

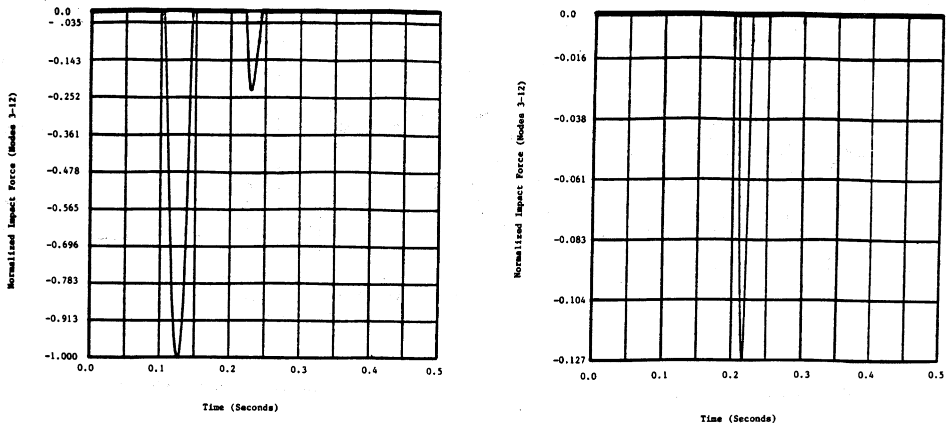
Figure 4 Normalized Relative Displacement (Nodes 2-5)



a) $\mu_D = 0.0$

b) $\mu_D = 0.15$

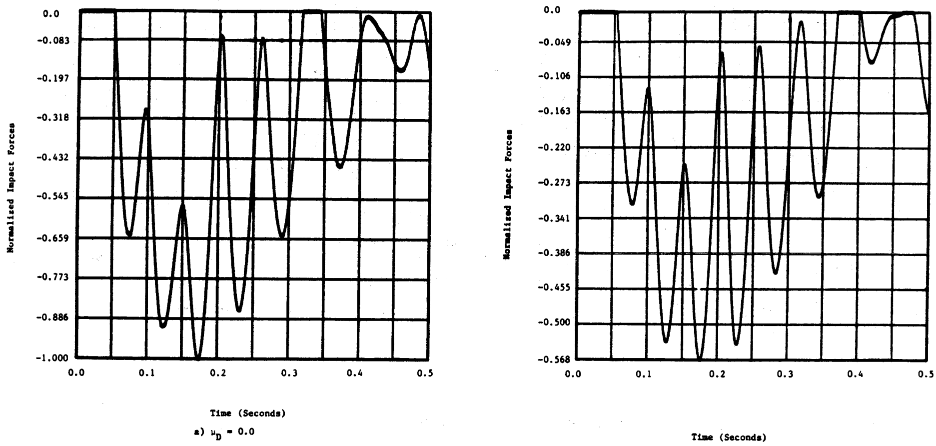
Figure 5 Normalized Relative Displacement (Nodes 3-12)



a) $\mu_D = 0.0$

b) $\mu_D = 0.15$

Figure 6 Normalized Impact Force (Nodes 3-12)



a) $\mu_D = 0.0$

b) $\mu_D = 0.15$

Figure 7 Normalized Impact Forces between Fuel Assembly and Core Barrel