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RESPONSE OF A BWR MARK II CONTAINMENT STRUCTURE TO CHUGGING LOADS

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Abstract

This paper presents an exact formulation for computing the containment structure/reactor building responses to chugging loads. The solution is obtained in two steps. First, the coupled downcomer vents-suppression pool system is analyzed assuming rigid boundaries. The steam in the vents and the water in the suppression pool are modeled as acoustic (compressible) fluids and excited by impulsive forcing signals applied at steam-water interface. Free water surface effects are accounted for and compatibility and continuity conditions are ensured at steam-water interface. The effects on the containment structure/reactor building are obtained from this step as an equivalent set of frequency dependent incident pressures and hydrodynamic (added) masses defined at water pool-containment structure interface (fluid-structure interface) using the finite element method. The containment structure/reactor building responses are then obtained adding frequency dependent hydrodynamic masses to the structure subjected to frequency dependent incident pressure loading applied over its wetted perimeter. The dynamic analysis is performed in the frequency domain using the finite element method. Transfer functions are directly defined for all required responses.

This two-step approach presents the advantage of an economical, yet exact solution: the 3-D dimensional downcomer vents-suppression pool system is solved first, then the responses of the axisymmetric containment structure are obtained using Fourier decomposition.

The response of a typical Mark II steel containment structure/reinforced concrete reactor building to an assumed chugging loading were obtained and results at selected critical locations are presented and discussed. It was found that the presence of steam in downcomers and the water pool affect considerably the structural responses.

1. Introduction

For BWR plants following a postulated loss-of-coolant accident (LOCA) event steam flows through the vent system and condenses at steam-water interfaces near vent exits thus limiting the containment pressure build-up within specified design limits. During high/medium steam mass flow rates, the condensation is steady and stable; later at low flow rates the condensation becomes unstable. During this later phase named "chugging," impulsive forcing signals are introduced into the suppression pool near vent exits,[1].

These forcing signals travel through the water of the suppression pool and, after reaching the pool boundaries, act as loadings on the containment structure. The design of the containment structure must account for the hydrodynamic loads due to chugging with due consideration to the presence of the pool of water.

2. Formulation of the Problem

A cross-sectional view of a typical BWR containment of Mark II configuration is shown in Figure 1. The containment includes the drywell and the wetwell separated by the drywell floor, but communicating through a large number of vertical vent pipes. During chugging, impulsive forcing signals are applied in a relatively random fashion, both in terms of intensity and time of occurrence, over the steam-water interfaces at vent exits. These forcing signals excite the steam in the vents and the water in the pool, the excitations travel through water and, reaching the pool boundaries, act as loadings on the containment structure. Let us define this loading as the incident pressure, p_i. During application of p_i the containment structure deforms while interacting with the water in the suppression pool and, as a result, induces in water a hydrodynamic pressure field, p. At the water-structure interface, Σ, this pressure acts as an added component of loading, $\underline{p_\Sigma}$, for the containment structure,[2].

2.1 Coupled Formulation

The response of the containment structure is governed by equation (1):

$$\underset{\sim}{M}\,\ddot{\underset{\sim}{u}} + \underset{\sim}{C}\,\dot{\underset{\sim}{u}} + \underset{\sim}{K}\,\underset{\sim}{u} = (p_i + p_\Sigma)\,\underset{\sim}{D} \;; \qquad (1)$$

where: $\underset{\sim}{M}$, $\underset{\sim}{C}$ and $\underset{\sim}{K}$ are the structural mass, damping and stiffness matrices, respectively, $\underset{\sim}{u}$, $\dot{\underset{\sim}{u}}$ and $\ddot{\underset{\sim}{u}}$ are the structural response displacement, velocity and acceleration, respectively, and $\underset{\sim}{D}$ is a directional unit vector whose only non-zero components correspond to the direction normal to the wetted boundary of the wetwell.

The steam in the vents and the water in the suppression pool are assumed to be acoustic (linear, inviscid and compressible) fluids; their response is governed by equations (2) and (3):

$$\nabla^2 p = (1/c^2)\,\ddot{p} \quad ; \qquad (2)$$

$$\dot{\underset{\sim}{v}} = -(\underset{\sim}{\nabla} p)/\rho \quad ; \qquad (3)$$

where: p, $\underset{\sim}{v}$ and ρ are the dynamic pressure, velocity and density of the fluid, c is the velocity of sound propagation in fluid, $\underset{\sim}{\nabla}$ is the gradient operator, ∇^2 is the Laplace operator and dots represent differentiation with time. In equation (2), when applied to steam in vents, the Laplace operator simplifies to a 1-D differential operator.

The boundary conditions to be satisfied reflect the following:

i) at the free pool water surface the dynamic pressure is zero;

ii) at water-structure interface continuity (which ensures uniqueness of solution) requires that the normal component of water velocity there equals that of the structure; in view of equation (3) this continuity condition becomes:

$$(\partial p_w/\partial n) = -\rho_w\,\ddot{u}_n \quad ; \qquad (4)$$

where: n is the direction normal to the interface, $\ddot{u}_n$ is the normal component of structural acceleration and the subscript w refers to water;

iii) at steam-water interfaces, i.e., at the suppression pool end of each vent, the chugging load is specified as an impulsive forcing function and thereafter pressures and velocities are maintained equal across the interface in water and steam;

iv) at the drywell end of each vent the dynamic pressure of the steam is zero there (recognizing that the drywell presence is equivalent to that of an infinite reservoir);

v) at the structure-foundation material interface appropriate support conditions are specified, depending on the foundation material properties.

The structure, the steam in the vents and the water in the suppression pool are assumed to be initially at rest and the dynamic pressures in steam and water nil.

2.2 Hydrodynamic (Added) Mass

It was shown (reference [3]) that the induced dynamic pressure at water-structure interface may be expressed in the frequency domain, after appropriate spatial transformations, by equation (5):

$$P_{\Sigma}(\omega)\,\underset{\sim}{D} = -\underset{\sim}{M}_F(\omega)\,\ddot{\underset{\sim}{U}}(\omega) . \qquad (5)$$

Using equation (5), equation (1) becomes in the frequency domain:

$$(\underset{\sim}{M}+\underset{\sim}{M}_F(\omega))\ \ddot{\underset{\sim}{U}}(\omega) + \underset{\sim}{C}\ \dot{\underset{\sim}{U}}(\omega) + \underset{\sim}{K}\ \underset{\sim}{U}(\omega) = P_i(\omega)\ \underset{\sim}{D}\ . \qquad (6)$$

In equations (5) and (6) $\underset{\sim}{M}_F(\omega)$ is the frequency dependent hydrodynamic (added) mass matrix and $P_i(\omega)$ is the frequency dependent incident pressure, $\underset{\sim}{U}(\omega)$, $\dot{\underset{\sim}{U}}(\omega)$ and $\ddot{\underset{\sim}{U}}(\omega)$ are the Fourier transforms of $\underset{\sim}{u}$, $\dot{\underset{\sim}{u}}$ and $\ddot{\underset{\sim}{u}}$, respectively, and $P_i(\omega)$ and $P_\Sigma(\omega)$ are the Fourier transforms of p_i and p_Σ, respectively. One notes that only in the case of a rigid containment structure $P_\Sigma(\omega)$ (or p_Σ) is identically zero since $\ddot{\underset{\sim}{U}}(\omega)$ (or $\ddot{\underset{\sim}{u}}$) is zero.

2.3 Solution of the Problem

The response of the containment structure to chugging is now conveniently and economically obtained in two steps:

Step 1 - Solve equation (2) with appropriate boundary conditions and assumed initial conditions for the specified forcing signals, in the frequency domain, and obtain frequency dependent incident pressure, $P_i(\omega)$, and frequency dependent hydrodynamic (added) mass matrix, $\underset{\sim}{M}_F(\omega)$; and,

Step 2 - Solve equation (6) with appropriate boundary conditions and assumed initial conditions to obtain structural responses (displacements, velocities and accelerations) in the frequency domain; an inverse Fourier transformation provides the responses in the time domain as well.

Use of the finite elements method is indicated for complex containment system geometries.

3. Single Vent Design Load Specification

Chugging tests were performed in a full scale single vent test facility, whose schematic representation is shown in Figure 2. These tests were designed to be representative of the postulated LOCA events (including the chugging phase) as they would affect a unit cell in a Mark II containment, i.e., a single vent with the afferent portion of the drywell and wetwell. Due to practical limitations, the forcing signals imparted to the suppression pool near vent exits could not be measured; instead the total hydrodynamic pressure (the sum of the incident and the induced/interactive pressures) was recorded at different locations on the suppression pool boundary. A study in the frequency domain of the recorded pressure traces has indicated the random nature of chugging loads, as represented by these traces. Since a sufficiently large sample size was available from tests, a statistical analysis of recorded pressure traces was implemented using their Fourier spectra and, alternately, their response spectra*. The latter represented the advantage

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* A response spectrum is a plot of the maximum response of a single-degree-of-freedom dynamic system of varying natural frequency and specified damping, when excited by a pressure trace, versus its natural frequency.

of being less sensitive to the time window used in computing them and being represented by smoother curves. As a result, it was possible to determine a design level response spectrum at the desired/required probability of non-exceedence limit and confidence level.

It was then required to define an impulsive forcing signal which when applied over the steam-water interface at vent exit would result in a calculated total hydrodynamic pressure at the suppression pool boundary whose response spectrum envelopes the design level response spectrum for the frequency range of interest, usually 0 to 150 Hz. This was accomplished by trial-and-error.

The analytical procedures described in Section 2. were used to define this impulsive forcing signal. Our studies have indicated that the following test facility components are critical and must be incorporated in the mathematical model of the test facility:

i) the vent acoustics (vent length, properties of contained steam considered an acoustic fluid, adequate boundary conditions at drywell vent end and at steam-water interface);

ii) the suppression pool (pool geometry, properties of water considered an acoustic fluid, adequate boundary conditions at free water surface, at steam-water interface, and at water-structure interface);

iii) the tank structure and its supports (the dynamic properties: stiffness/flexibility, mass and damping, adequate boundary condition at water-structure interface).

It was found that if all these components were properly accounted for, then the analytical model can reproduce reasonably well the recorded behavior of the test facility during chugging.

4. Mark II Containment Structure Response to Chugging Loads

A Mark II steel containment structure similar to that shown in Figure 1 was analyzed for chugging loads. During the chugging phase, which occurs near the tail-end of a postulated LOCA event, since conditions within containment (drywell, wetwell, and connecting vents) are expected to be rather uniform, it appears rational to apply the same impulsive forcing signal at all vent exits. In view of the large number of vents and the random character of the load a design level load corresponding to a statistical statement of 50% probability of non-exceedence limit and 97.7% confidence level appears appropriate. (These values correspond to mean and mean plus two standard deviations for a normal distribution, respectively). The forcing signals are assumed applied simultaneously, i.e., in phase, a conservative assumption considering the random nature of the load with respect to time of occurrence.

The response of the containment structure to chugging loads, defined hereinabove, were obtained using the analytical procedures outlined in Section 2. Responses at two critical locations, the containment structure at an elevation corresponding to mid-submergence of vents and the pedestal at RPV support elevation, are plotted in Figures 3 and 4, respectively. The responses are expressed as acceleration response spectra. For comparison purposes, responses at same locations were obtained assuming the chugging load to be represented by typical pressure traces (at mean intensity) recorded on the wetted boundary of the test facility. It is evident from Figures 3 and 4 that improper definition of chugging loads could result in unrealistic, but not necessarily conservative results throughout the entire frequency range.

5. Summary and Conclusions

A rational and practical method for the analysis of BWR containment structures subjected to chugging loads is presented. This method is based on statistical evaluation of existing full-scale single vent test data, recognizing the random nature of chugging loads, from which a single vent design load specification is obtained. The design load, an impulsive forcing signal, is defined over the steam-water interface at vent exit. The impulsive forcing signal is then uniformly distributed to all vent exits in a BWR containment of Mark II configuration. This uniform load distribution pattern is considered representative of rather uniform conditions established within containment during chugging.

The analysis of the containment structure is performed economically in the frequency domain in two steps: first, frequency dependent incident pressure wave and hydrodynamic (added) masses are obtained, and then, the containment structure response is obtained.

In this analysis all significant containment components (steam in the vents, suppression pool and structural containment boundary) are represented, and critical effects (vent acoustics, pool acoustics and pool-containment structure interaction effects, etc.) are accounted for.

If chugging loads are improperly defined and/or are inadequate analysis of the containment structure is implemented one may obtain unrealistic results; such results may not be conservative in the frequency range of interest.

Acknowledgement

The authors are indebted to Mrs. W. R. Smith for her expert typing.

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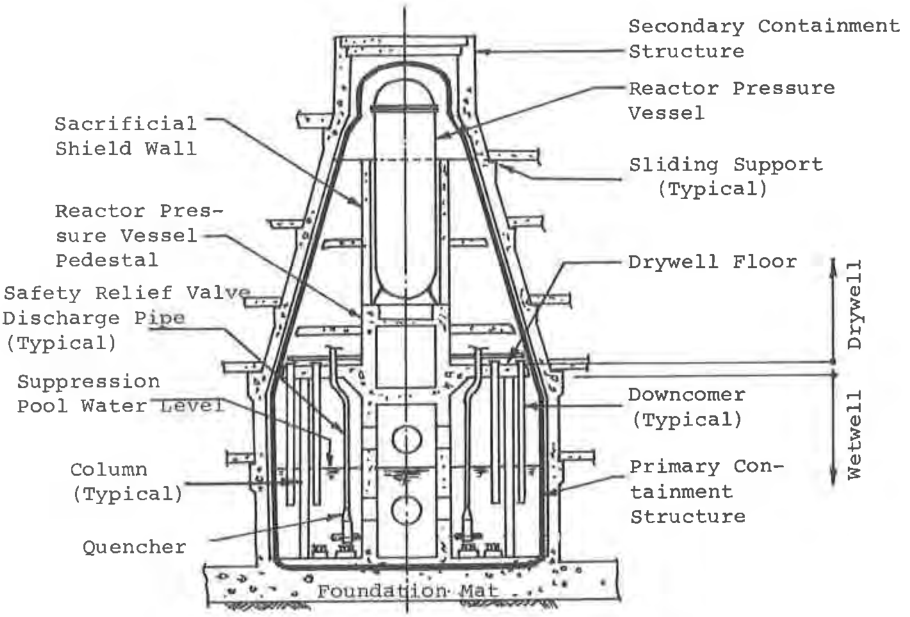

Figure 1 Mark II Containment: Cross Sectional View

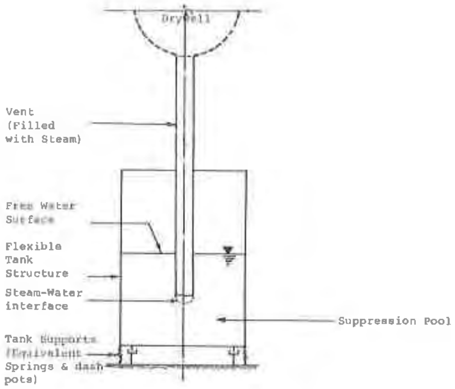

Figure 2 Single Vent Test Facility: Schematic representation

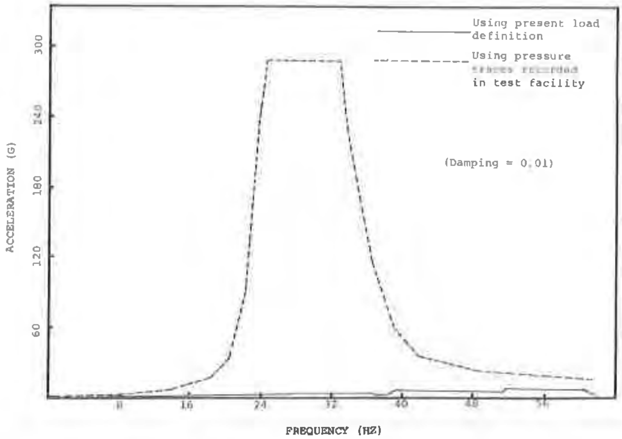

Figure 3 Mark II Containment response to chugging loads: Containment wall at vent mid-submergence elevation

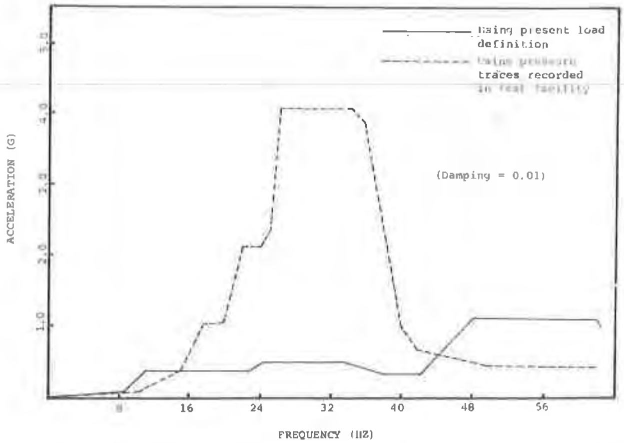

Figure 4 Mark II Containment response to chugging loads: Pedestal at RPV supports