Evaluation of Dynamic Loads Induced by Chugging

Mutsuhiro ARINOBU, Isamu SUZUKI,
Toshiba Research and Development Center, Toshiba Corp.*

Eiji SHIHO and Hideto AOKI
Nuclear Energy Group, Toshiba Corp.**

Received May 4, 1982

A dynamic load evaluation method has been proposed for chugging phenomena which are assumed to occur and produce relatively large amplitude pressure spikes in the pressure suppression pool of a BWR containment, in case of a postulated loss of coolant accident. The proposed method is based on the analysis code developed by the authors and on the seven vent full scale tests performed at Japan Atomic Energy Research Institute (JAERI CRT), considering random nature of chugging phenomena. The dynamic loads are obtained by applying the design source functions of impulsive nature to the vent pipe exists in each BWR containment analysis model. The design source functions are defined to produce dynamic pressures which reasonably envelope the design spectrum based on JAERI CRT data in frequency domain.

As an application example, the dynamic loads induced by chugging have been assessed based on the proposed method and on the reported JAERI CRT data from the view point of conservative load evaluation.

The applicability of the analysis code has also been confirmed, since the simulated dynamic pressures have shown features and magnitudes similar to those observed in JAERI CRT.

KEYWORDS: BWR type reactors, pressure suppression containment, loss of coolant, dynamic loads, steam condensation, chugging, computer codes, computer calculations

I. INTRODUCTION

During a postulated loss of coolant accident (LOCA), chugging phenomena are assumed to occur which produce relatively large amplitude pressure spikes in the pressure suppression pool in a boiling water reactor (BWR). Chugging phenomena observed in small scale experiments are intermittent condensation events which occur at low steam flow rates and generally produce negative pressure followed by positive pressure spikes and damping pressure oscillation (ring-out). The negative pressure is caused by rapid condensation of steam, while positive pressure spikes are mainly induced by steam bubble collapse phenomena. This dynamic pressure causes dynamic loads on the containment boundary and structures in the suppression pool.

It is important to evaluate the dynamic loads induced by chugging in order to warrant the BWR containment integrity even in the case of a LOCA. On one hand, the Mark II containment response test (CRT) program is ongoing at the Japan Atomic Energy Institute (JAERI) for the investigation on the LOCA hydrodynamic loads induced in the BWR Mark II containment systems. The tests, called JAERI CRT, have been performed using 20° sector model containment with seven vent pipes. The JAERI CRT results have

** Shinsugita, Isogo-ku, Yokohama 235.
clarified many important features of condensation phenomena under full scale conditions. From the viewpoint of dynamic load evaluation, one of the most important factors is that the dominant frequency components of induced dynamic pressure in the pool are correspondent with those expected to be caused by pressure wave propagation and reflection in the vent system\(^{(5)}\). On the other hand, an analysis code ACERON has been developed by the authors\(^{(4)}\) in order to evaluate the dynamic loads caused by chugging based on the data obtained in the 'full scale' tests.

This paper describes the dynamic load evaluation methodology proposed by the authors, based on the analysis code and 'full scale' test results.

Such a methodology is necessary in order to assess the dynamic loads on real BWR containments which have different vent system and suppression pool dimensions including pool water levels from those of the 'full scale' test facilities.

### II. Analytical Model

The dynamic pressure induced by chugging is assumed as shown in Fig. 1\(^{(4)}\). That is, the hydrodynamic perturbations induced by steam condensation at the steam vent pipe exits excite the pressure field in the vent pipes as well as in the pool and both excited pressure fields cause the dynamic pressure in the pool. The dynamic pressures induced in the vent pipes are easy to be transferred through the steam/water interfaces. Those in the pool cannot be so easily transferred because of the density difference between steam and water, which is the reason why the feedback from the pool to vent are shown by dotted line and this feedback is not taken into account here in the calculation of the dynamic pressure.

Considering the thermal hydraulic conditions under which chugging phenomena are assumed to occur in the pressure suppression pool, there may be many small air bubbles which are separated from water in the pool by temperature rise or which might come from the drywell. As sonic velocity in the water containing many small air bubbles is thought to be markedly reduced, compressibility of water should be taken into account in order to investigate the dynamic pressure caused by chugging in a pool as large as a BWR containment. In analysis code ACERON, the acoustic wave equation is assumed to govern the fluid flow in the pool, that is,

\[
\left( \nabla^2 - \frac{1}{C_w^2} \frac{\partial^2}{\partial t^2} \right) p(r, t) = f(r, t),
\]

where \( p(r, t) \) is the dynamic pressure, \( f(r, t) \) the contribution of bubble collapse or oscillation, \( \nabla^2 \) the Laplacian, and \( C_w \) the sonic velocity in water. Boundary conditions are as follows:

\[
\frac{\partial p}{\partial n} = 0 \quad \text{at the pool boundary},
\]

\[
p = 0 \quad \text{at the free surface},
\]

where \( n \) means normal at the boundary. Equations (1)~(3) have been solved analytically for the sector of a concentric cylinder using eigenfunctions. The details of the solution
are shown in Ref. (4).

On the other hand, pressure waves in the vent pipes are assumed to be one-dimensional in space. The dynamic pressures in the vent pipes are solved by the method of characteristics, that is,
\[ \pm \frac{1}{C_s} \frac{dp}{dt} + \rho_s \frac{dv}{dt} + \frac{\rho_s F}{2D} |v|v=0, \frac{dx}{dt} = \pm C_s \]  
(4)
are solved numerically, where \( p=p(x, t) \) is the dynamic pressure, \( v=v(x, t) \) the steam velocity, \( C_s \) the sonic velocity in steam, \( \rho_s \) the steam density, \( D \) the inner diameter of a vent pine, \( F \) the friction factor, and \( x \) the distance along the vent pipe axis.

Equations (1)~(3) and (4) are coupled by the source functions applied at the vent pipe exits. The condition at the steam/water interface is given as
\[ p(x, t) \bigg|_{z=0} = \frac{\rho_w}{4\pi R} \frac{dm(t)}{dt}, \]  
(5)
where \( \rho_w \) is the water density, \( m(t) \) the strength of the source, and \( R \) the radius of equivalent sphere for steam/water interface.

The dynamic pressure observed in JAERI CRT has been simulated by ACERON in order to confirm the applicability of the analytical model for dynamic load evaluation. The containment configuration modeled for the calculation is shown in Fig. 2 and simulation examples are shown in Fig. 3, respectively. The dynamic pressures in the pool shown in Fig. 3 have been simulated by applying five source functions of impulsive nature to seven vent pipe exits. These five source functions can be defined to simulate the observed...

---

**Fig. 2** Analysis model for JAERI CRT facility

**Fig. 3** Comparison between calculated and experimental pressure time histories in suppression pool
dynamic pressure in each vent pipe, because dynamic pressure has been measured in five of seven vent pipes in JAERI CRT. Source functions for two vent pipes, where dynamic pressure has not been measured, are assumed to be same as those for the neighboring two vent pipes. The calculated pressure time histories in the pool show features similar to the measured ones without some spikes of very high frequency as shown in Fig. 3, in spite of the uncertainty about the two source functions.

III. DYNAMIC LOAD EVALUATION METHOD

The applicability of the analysis code has been confirmed for evaluating the dynamic pressure induced by chugging by simulating JAERI CRT results. If all BWR Mark II containments have the same dimensions, including water level in the pressure suppression pool, as JAERI CRT containment and if every LOCA condition has been simulated in JAERI CRT tests for each BWR Mark II plant, dynamic responses for real containments can be assessed without such an analysis code by applying the dynamic loads observed in JAERI CRT directly to the real containments. However, the BWR Mark II containment dimensions differ from one plant to the other, which causes a difference in the frequency components of resultant pressure induced by chugging.

The dynamic load evaluation methodology for conservative and reasonable load assessment is proposed here.

Assumptions are as follows:
(1) Condensation phenomena observed in ‘full scale’ tests are the same as those in real containments, if both thermal-hydraulic conditions are equivalent.
(2) Chugging phenomena are of random nature.
(3) Dynamic responses of structures depend on the frequency components and their magnitudes of dynamic pressure on the structures.
(4) The severest response is obtained under the symmetrical load condition.

Under these assumptions, dynamic loads are defined based on the analysis code and JAERI CRT results, as follows:
(1) Calculate PSD (Power Spectral Density) or RS (Response Spectrum) from the observed pool boundary pressure for each chugging in JAERI CRT.
(2) Define the design spectrum (PSD or RS) by statistical analyses of obtained PSDs or RSs from the view point of conservative and reasonable load evaluation.
(3) Calculate dynamic pressure by applying source functions to seven vent pipe exits for the JAERI CRT containment analysis model.
(4) Calculate PSD or RS from calculated pressure.
(5) Compare the calculated PSD or RS values with the design spectrum.
(6) Repeat (3)~(5) until calculated spectra envelope design spectrum reasonably.
(7) Design source functions are defined by repetition of Steps (3)~(6).
(8) Calculate dynamic pressure in real containments by applying the design sources to the vent pipe exits for each BWR containment analysis model.

The dynamic response of structures are calculated by applying the obtained dynamic pressure to the structures.

Figure 4 shows the dynamic load evaluation process mentioned above.

IV. EXAMPLE OF LOAD EVALUATION

The dynamic loads due to chugging are evaluated here for a representative Mark II
containment in order to show an application example of the proposed methodology.

Test 0002 has been chosen as representative from the JAERI CRT data which have already been reported now, for the following reasons:

1. Many severe chugging, which produced large amplitude dynamic pressure, were observed.

2. Deviations in the dominant frequency of the dynamic pressure are relatively large from one chug to the other.

The design spectrum example is defined as follows:

1. Select six largest chugs and two chugs adjacent to the largest of the six. (Conservatism)

2. Calculate PSD values for dynamic pressure at each measuring point for eight chugs.

3. Define representative PSD values for eight chugs by averaging slightly different PSDs obtained at the walls 3.6 m from the bottom. (reasonability for symmetrical loads)

4. Define design spectrum by an enveloped PSD of the eight representative PSDs.

The reason why the dynamic pressure measured at 3.6 m height walls has been chosen is that this height corresponds to the vent pipe exit height and pressure transducers at this height have no troubles.

As pointed out in earlier studies, chugging phenomena occur rather randomly from one vent pipe to the other. The obtained design spectrum or each representative PSD is based on the resultant pressure, including the influence of random chugging events at seven vent pipe exits. On the other hand, if chugging occur randomly at every vent pipe exit of a real containment, which has more than 100 vent pipes, it should be reasonable to assume that the resultant symmetrical load is a kind of averaged load resulted from random chugging events at more than 100 vent pipes exit. However, the example design spectrum has been defined by enveloped PSD instead of an averaged PSD for eight representative PSD values mainly because of the base data limitation and from the view point of conservative load evaluation.

The dynamic pressures have been calculated at a point corresponding to the design spectrum by applying the same source functions to seven vent exits for the JAERI CRT analysis model. The source function example has been defined as shown in Fig. 5 by...
comparing the calculated PSDs with the design spectrum. Figure 6 shows a comparison between the design spectrum and enveloped PSD obtained by design source. An example of a calculated pressure time history and its PSD is shown in Fig. 7. In order to envelope the example design spectrum reasonably, three different sonic velocities in steam, 285, 326 and 407 m/s, have been used. Such deviations in sonic velocity have also been observed in base data for design spectrum from one chug to the other as deviations in dominant frequency components assumed to result from pressure oscillations in vent pipes, and may occur in a LOCA hypothesized in a real containment.

Dynamic pressures have been calculated and the results are shown in Fig. 8(a)~(c) for a representative Mark II containment which has slightly different suppression pool dimensions and vent pipe length from the JAERI CRT containment, applying the example design source function with different sonic speeds in steam to the vent pipe exits completely in phase. It is reasonable to expect that the sonic velocity in steam also deviates in the same manner in real containments as observed in JAERI CRT. Three different sonic velocities in steam, 285, 326 and 407 m/s, which have been used in order to envelope the design spectrum reasonably, have also been used to calculate the dynamic pressures in a real containment. As the dynamic pressures induced by the design source function can be calculated at any point in the pressure suppression pool, dynamic responses
of the structures can be obtained by applying these dynamic pressures to the structures.

![Figure 8(a)](image1)

![Figure 8(b)](image2)

![Figure 8(c)](image3)

(a) \(C_s = 285 \text{ m/s}\)

(b) \(C_s = 326 \text{ m/s}\)

(c) \(C_s = 407 \text{ m/s}\)

Fig. 8(a)–(c) Calculated pool bottom pressure in Mark II containment by design source

V. CONCLUSION

A dynamic load evaluation method has been proposed for chugging phenomena, based on the analysis code and JAERI CRT results.

An example of dynamic load evaluation has also been shown for a representative Mark II containment, based on the proposed methodology.
The reasonability of the proposed methodology depends on applicability of the analysis code and the reasonability of the design spectrum. The former has been confirmed by simulating JAERI CRT results. The latter has not been sufficiently investigated because of the data limitation.

ACKNOWLEDGMENT

The authors wish to express their thanks to Prof. T. Saito of University of Tokyo, Assoc. Prof. H. Nariai of University of Tsukuba, Mr. M. Shiba, Dr. Y. Kukita and other persons of Safety Research Laboratory I, Japan Atomic Energy Research Institute, for their kind discussions.

REFERENCES