Fluid-Structure Coupled Dynamic Response of PWR Core Barrel during LOCA

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ABSTRACT

This paper is engaged in the Fluid–Structure Interaction LOCA analysis of the core barrel of PWR. The analysis is performed by a multipurpose computer code SANES. The FSI inside the pressure vessel is treated by a FEM code including some structural and acoustic elements. The transient in the primary loop is solved by a two–phase flow code. Both codes are coupled one another. Some interesting conclusions are drawed.

1 INTRODUCTION

The urgent energy requirement of the modernization of industry promotes a rapid development of nuclear reactors in P.R. China. The nuclear safety technology becomes more and more important for our country.

The loss–of–coolant accident (LOCA) is the most seriours accident of the pressurized–water–reactor (PWR). A lot of experimental, computational and theoretical investigations in this area are performed and have been reported in the papers of SMiRTs and in some Jounals. The well–known one is the HDR Safety Program in the Federal Republic of Germany (Schlechtendahl, 1979; Bader et al. 1985). Some computational researches are also reported from USA (Belytschko et al. 1985), France (Guilbaud, 1987), Japan (Sakurai et al. 1985) etc.

This paper is engaged in the Fluid–Structure Interaction (FSI) LOCA analysis of the core barrel of a Chinese 2–loop PWR. The analysis is performed by a multipurpose code SANES (Safety Assessment of Nuclear Engineering Structures) developed by the Beijing University and the Tsinghua University. The FSI–LOCA subprogram of SANES consists of two parts. One part, which is used to treat the fluid–structure coupled response inside the pressure vessel, is a displacement–based FEM code including isoparametric shell element, isoparametric beam element, 3–D solid element and acoustic 3–D fluid element. Other part, which is used to deal with the transient flow in the primary loop of PWR, is a 1–D two–phase flow code using the discrete bubble model and the method of characteristics. The coupling variables on the interface of pressure vessel (PV) with primary piping (PP) are the pressure and the velocity of fluid.

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2 FSI ANALYSIS OF LOCA

The core barrel is a thin–walled cylindrical shell embedded in the subcooled water and excited by the rarefaction wave traveling in the surrounding water; Its deformation has direct influence on the transient flow inside the pressure vessel. In recent years many FSI computer codes are developed to simulate the dynamic response of the core barrel during LOCA.

Some special FSI codes are based on the Finite Difference Method, such as FLUX–2, K–FIX mentioned by Belytschko et al. (1985). As a multipurpose code we select the Finite Element Method. The displacement–based FEM codes have been widely used in the structural analysis. The FSI–LOCA subprogram of SANES contains three kinds of structural element:

- isoparametric shell element
- isoparametric beam element
- isoparametric or subparametric 3–D solid element.

The linear and nonlinear analysis of dynamic or static problems can be performed with these structural elements.

According to the following reasons, the fluid field inside the pressure vessel of PWR is modeled by the acoustic 3–D fluid elements:

(1) It is an inner fluid field walled by the pressure vessel. The disturbance, which is caused by the rarefaction wave during LOCA and superposed on the steady flow of the normal operation, is small.

(2) The viscosity of subcooled water can be negligible.

(3) It can be assumed that at the inital stage of LOCA the depressurization does not cause the subcooled water inside the pressure vessel to vaporize, and the two–phase flow happens only in the primary loop. This assumption is often appropriate, if the break of primary piping appears at a distance from pressure vessel.

There are three formulations to deal with the acoustic–fluid problem by finite element methods:

- displacement formulation
- pressure formulation
- velocity potential formulation.

We select the first one, whose advantages are

(1) symetric system of equations

(2) easier connection with the displacement–based structural elements

(3) extensive suitability for the dynamic or static coupled system, the sloshing problem, etc.

It is worth notice that for the displacement formulation the singularity of matrix may be sometimes arise from the rotation modes of fluid (Wang, 1990).

Using the displacement formulation the discrete FEM equation of a fluid–structure coupled system is

$$\begin{bmatrix} \mathbf{M}_s & \mathbf{O} \\ \mathbf{O} & \mathbf{M}_f \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_s \\ \ddot{\mathbf{u}}_f \end{bmatrix} + \begin{bmatrix} \mathbf{K}_s & \mathbf{O} \\ \mathbf{O} & \mathbf{K}_f \end{bmatrix} \begin{bmatrix} \mathbf{u}_s \\ \mathbf{u}_f \end{bmatrix} = \begin{bmatrix} \mathbf{F}_s \\ \mathbf{F}_f \end{bmatrix}$$

where M — mass matrix
K — stiffness matrix
F — vector of external forces
$\mathbf{u}$ — nodal displacement vector
$\ddot{\mathbf{u}}$ — nodal acceleration vector

$(\ )_s$ — structure
$(\ )_f$ — fluid

The coupling of fluid to structure is introduced by the compatibility condition of normal displacemen at the interfaces of the fluid domain with the solid body.

Once a break appears in the primary piping, the depressurization will cause a part of subcooled water nearby the break to vaporize. Therefore we simulate the transient flow in the primary loop of PWR by a 1–D two–phase flow code (He, 1988). There are quite a few models to characterize the two–phase flow phenomenon. We employ the discrete bubble model, in which the following hypotheses are applied:

(1) There is no slip between the two phases

(2) The bubbles are concentrated on the calculating cross–sections, whose position can adjust according to the number of calculating segments.

(3) Between the calculating cross–sections there is only the pure liquid, in which the wave velocity is constant.

(4) The transient is an isothermal process.

The FEM code and the two–phase flow code can be coupled or decoupled. In the decoupled analysis the transient pressure on the interface of PV with PP is obtained from the two–phase flow analysis, in which the pressure vessel is treated as a fluid volume. Then the dynamic response of the core barrel is obtained from the FEM analysis, in which the above mentioned transient pressure is given as an external load on the interface. In the coupled analysis the coupling variables are the pressure and the mean velocity at the interface. The mean velocity obtained from FEM analysis will be sent return to the two–phase flow analysis to correct the initial condition of the fluid analysis.

3 DYNAMIC RESPONSE OF CORE BARREL

As an example the core barrel of the Qin–Shan Nuclear Power Plant, which is a 300MW 2–loop PWR in P.R.China, is analyzed.

The core barrel is modeled with 8–node isoparametric shell elements. Its upper end is clamped. The mesh of shell elements in the neighbourhood of the blowdown nozzle is refined. The core is represented by a massring at the lower end of core barrel to simulate its inertial influence on the structural dynamic response and by a rigid cylinder at the centre of core to simulate its clogging influence on the fluid dynamics. The massring is modeled with 3–node isoparametric beam elements, whose stiffness is defined to simulate the supporting effect of the lower tie plate.

The pressure vessel is considered as a rigid wall surrounding the subcooled water. The fluid inside the pressure vessel is modeled with 20–node 3D acoustic fluid elements. According to the compatibility condition both the normal displacements of the fluid node and the corresponding structural node are equal one another, but the tangential slip is allowable.

Because of the symmetric arrangement of two loops only half of the system including a inlet and a outlet is modeled. In the symmetry plan through the central axis of pressure vessel the symmetrical conditions are prescribed.

In the guide lines of the German Reactor Safety Commission two classes of LOCA have to be considered:

(1) The sudden, double–ended rupture of a primary coolant pipe (2A–break), which is the most serious accident, but its probability is smaller.

(2) The 10% area break of a primary coolant pipe with an intermediate break openning time (0.1A–leak), whose probability is larger.

Both the conditions are analyzed here. It is assumed that the break appears at a distance 3m from the pressure vessel. The curves of the pressure transient are given in Fig.1.

In order to observe the influence of outlet both conditions, with outlet and without outlet, are calculated.

The maximum response of the core barrel occurs at the central point opposite the blowdown nozzle. The curves of time history of the normal displacement, the normal acceleration and the von Mises stress at this point are given in Fig.2~4.

Figure 2 is the results of the 2A–break condition. Figures 3, 4 correspond to the conditions of 0.1A–leak with outlet and 0.1A–leak without outlet separately.

The deformed shape of the core barrel is similar to Fig.9 given by Bader (1985), and omited here.

4 CONCLUSION

The sustained jet–time of the subcooled water is 50ms for 2A–break and 200ms for 0.1A–leak with outlet. A sudden pressure drop from the normal operation pressure to the saturation pressure occurs in this stage. Then the pressure oscillates about the saturation pressure. This phenomenon of the global pressure drop is different from the HDR test because of the consideration of the actual subcooled water.

The step of time integration is taken as 2.78ms. It is fine enough for the two–phase flow analysis and for the dynamic response analyses of displacement and stresses. But more oscillations of the acceleration curve will appear, if the time step is further refined. For the FEM analysis in time 0.5~1.0 sec. the time step is four times enlarged.

The dynamic deformation of the core barrel consists of a global– and a local component. The period of the global vibration of core barrel in the water is 2.22 sec., about 60 times the period in the air. A hilly local vibration excited by the impact of the depressurization from inlet happens in the neighbourhood of the blowdown nozzle. The period of the local vibration is about 0.3 sec. (See the displacement history in Fig.2). The normal displacement of the central point opposite the inlet is 0.41 mm for 2A–break and 0.29mm for 0.1A–leak.

The initial stage of stress history seems to be an inverse curve of the pressure transient. It implies that the initial response is a forced vibration. The maximum stress with a value 124 MPa for 2A–break and 104 MPa for 0.1A–leak occurs at the central point opposite the inlet.

The dynamic response of the core barrel without outlet is about 12% lager than one with outlet.

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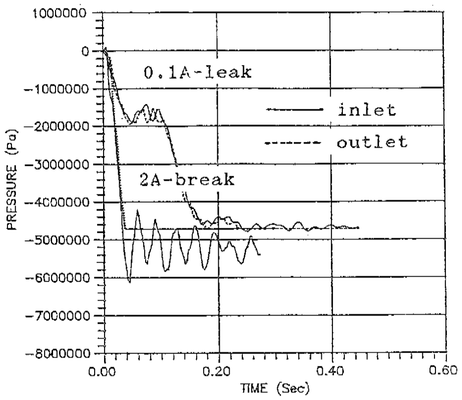
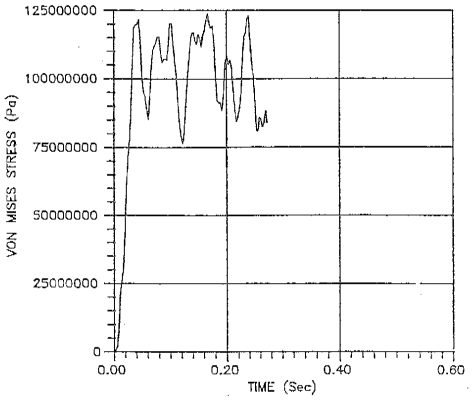
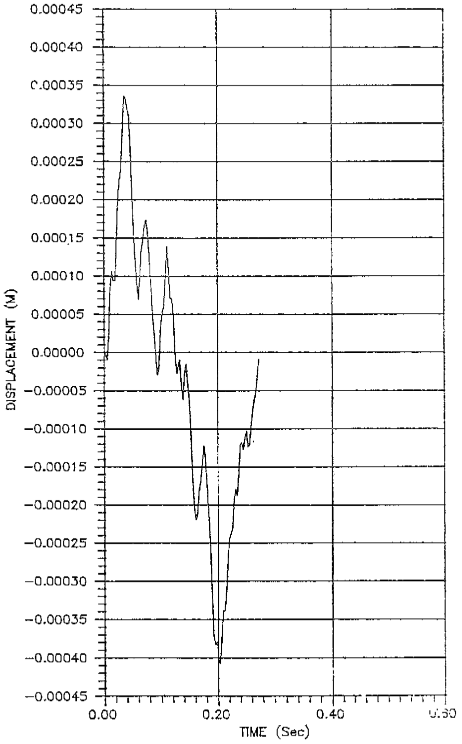
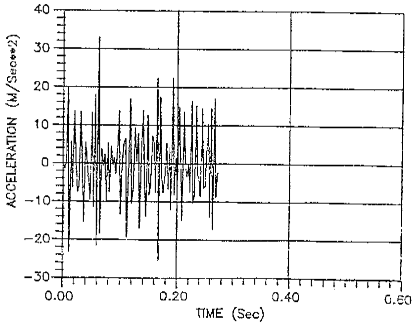


Fig.1 Pressure Transient



(b) von–Mises stress

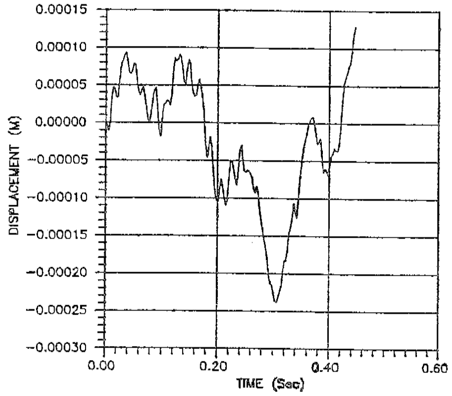




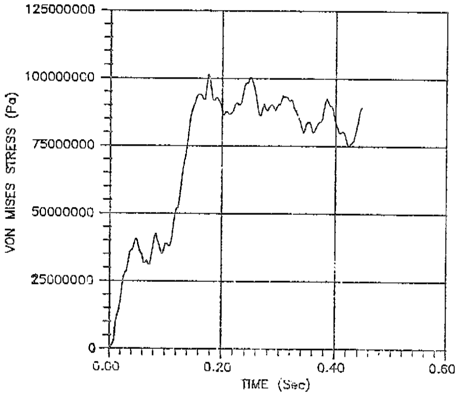
(a) normal displacement

(c) normal acceleration

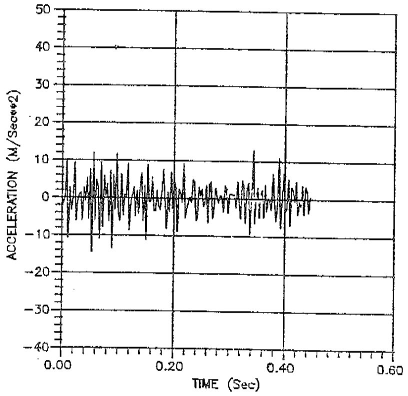
Fig.2 2A–Break Condition



(a) normal displacement

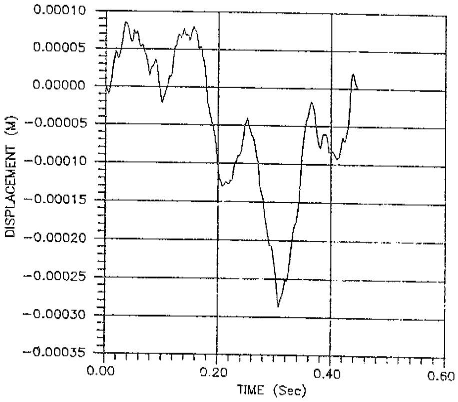


(b) von Mises stress

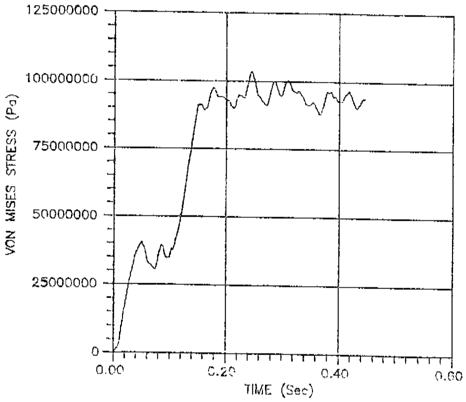


(c) normal acceleration

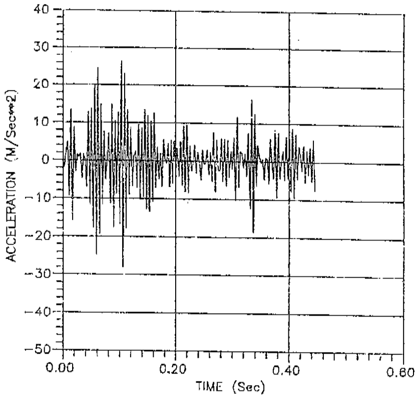
Fig.3 0.1A–Leak Condition
with Outlet



(a) normal displacement



(b) von Mises stress



(c) normal acceleration

Fig.4 0.1A–Leak Condition
without Outlet