FSI-9-2 2.3I IAEA Activities on Fluid Structure Interaction for Nuclear Power Plant

An Overview of Computational Method for Fluid-Structure Interaction

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Outline of Presentation

5.1 Introduction

5.2. Mathematical Equation and Numerical Modelling

5.3. Applications

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5.1. Introduction

- Prediction and analysis of FSI between structure and fluid flow requires information on **hydraulic loads**.
  - The flow-induced hydraulic loads on a structure can be **the random hydraulic loads produced by random turbulence of the coolant** such as pulsation of a reactor coolant pump, vortex shedding, and secondary flow (re-circulation) caused by a structure.
  - Hence, **flow field analyses** for practical applications are usually **too complex to solve analytically**.

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5.1. Introduction (cont'd)

- In addition, since the spaces occupied by the fluid and the structure may change as the FSI occurs,
  - a numerical analysis of FSI involves the **numerical solution of the Navier-Stokes equation** with **moving boundary conditions** and **their interactions with structures**.
- **Computational fluid dynamics (CFD) analysis** has made the numerical simulation of complex fluid flow possible so that it can be used to provide the flow field

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2. Mathematical Equation and Numerical Modelling

(1) Governing Equation

- The **continuity equation, momentum equation (Navier-Stokes Equation) and energy equation for a Newtonian compressible fluid flow** such as acoustic vibration and resonant fluid flow in a pipe.
- However, numerically solving the equations in practical applications **requires large computational resources** and is costly so that a further simplified analysis is applicable.

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2. Mathematical Equation and Numerical Modelling (cont'd)

(2) Turbulence Analysis Method

Standard - turbulence model

- Launder and Sharma (1974) suggested the standard - model, which is based on the **transport equations for the turbulence kinetic energy, and its dissipation rate**.
- The standard - model provides **good predictions** for many flows of engineering interest.
- However, one of the weaknesses of the standard - model is that it is **not sensitive to streamline curvature for flows with strong swirl, flow separation, secondary flow, and impinging jets**, so there are applications for which this model is not suitable.

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2. Mathematical Equation and Numerical Modelling (cont'd)

(2) Turbulence Analysis Method (cont'd)

RNG - turbulence model

- Renormalization group (RNG) - model was developed by Yakhot and Orszag(1986) and Yakhot et al. (1992) using renormalization group theory.
- The transport equations for turbulence kinetic energy and dissipation rate are the same as those for the standard - model **except the model constants**.
- The RNG - model has **an additional term and the effect of swirl** is considered in its equation to enhance the predictions for **rapidly strained flows and for swirling flows**.
- RNG - model provides more accurate predictions in a wider range of flow than the standard - model.

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2. Mathematical Equation and Numerical Modelling (cont'd)

(2) Turbulence Analysis Method (cont'd)

Reynolds stress turbulence model

- The Reynolds stress model (RSM) does not assume isotropic eddy viscosity but **solves an equation for the transport of Reynolds stresses together with an equation for the dissipation rate** to close the Reynolds-averaged Navier-Stokes equations.
- The RSM is the **most elaborate model and much more costly** than other models because the RSM solves the exact transport equations for the Reynolds stresses.
- RSM usually gives more accurate predictions for complex flows such as **swirling flows, rotating flows, secondary flows, and flow with rapid changes in strain rate are among them**, for instance.

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2. Mathematical Equation and Numerical Modelling (cont'd)

Large Eddy Simulation (LES)

- Turbulence can be characterized **by the length and time scales of eddie**s. The size of eddies ranges from the size of the physical domain (largest) to **Kolmogorov length scales** (smallest).
- The governing equations of LES are obtained by filtering the Navier-Stokes equations **to eliminate small scale eddies out of the solution** such as volume-average box filter, Fourier cut-off filter, and Gaussian filter, for instance.
- The LES is suitable for **flows when the flow is unstable** (e.g., vortex shedding), highly anisotropic turbulence is dominant, and fluctuating information is required (fluctuating forces, flow induced noise and vibration, for instance).

Kolmogorov length scale	$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$
Kolmogorov time scale	$\tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$
Kolmogorov velocity scale	$u_\eta = (\nu\epsilon)^{1/4}$

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2. Mathematical Equation and Numerical Modelling (cont'd)

Direct Numerical Simulation (DNS)

- The Navier-Stokes equation and mass conservation equation can be **directly solved without any turbulence model** if a complete set of boundary conditions are available.
- The size of the turbulent flow structures range from the very small **Kolmogorov scales** to integral scales of the size of the physical domain.
- The DNS resolves the whole range of spatial and temporal scales of the turbulence in the computational mesh so that a DNS requires **so fine a mesh** that **the computational cost is very high** even at low Reynolds numbers.

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2. Mathematical Equation and Numerical Modelling (cont'd)

Lattice-Boltzmann Method (LBM)

- The Lattice-Boltzmann Method (LBM) were invented by von Neuman in the late 1940s, and has made major progress since its first appearance in the middle of the 1980s.
- The LBM solves **the discrete Boltzmann equation** to simulate the flow of a Newtonian fluid with **collision models** instead of solving the Navier-Stokes equation.

Collision step: $f_i^t(\vec{x}, t+\delta_t) = f_i(\vec{x}, t) + \frac{1}{\tau_f}(f_i^{eq} - f_i)$

Streaming step: $f_i(\vec{x} + \vec{e}_i\delta_t, t+\delta_t) = f_i^t(\vec{x}, t+\delta_t)$

- The LBM approach has some limitations because **the stability and accuracy of the method is strongly affected by the characteristics of boundary conditions**. But it is difficult to specify the boundary conditions based on the conditions for physical variables.

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2. Mathematical Equation and Numerical Modelling (cont'd)

(4) Commercial CFD Code

- There are many commercial CFD software which is used in a wide spectrum of applications.
- These CFD codes have been validated against numerous single-phase benchmark tests so that modern commercial CFD codes produce sufficiently **reliable results in single-phase flow field analyses when proper turbulence models are used**.
- State-of-the-art commercial CFD codes **have limited capabilities in two-phase flow simulation**.
- Utilization of CFD in analysis of FIV caused by two-phase flow is not considered to be established or useful at present.

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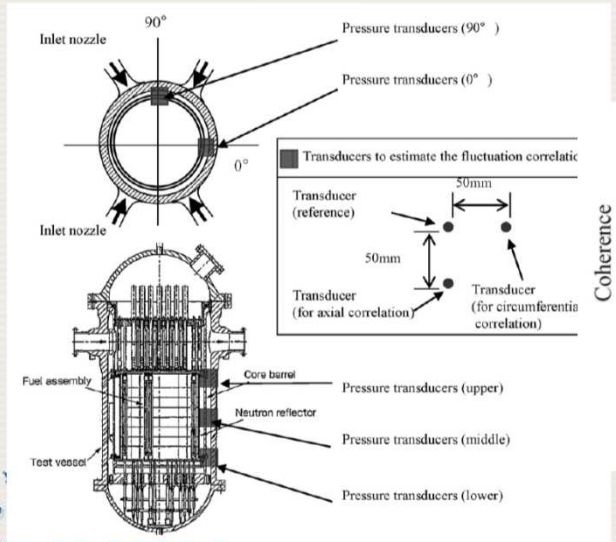
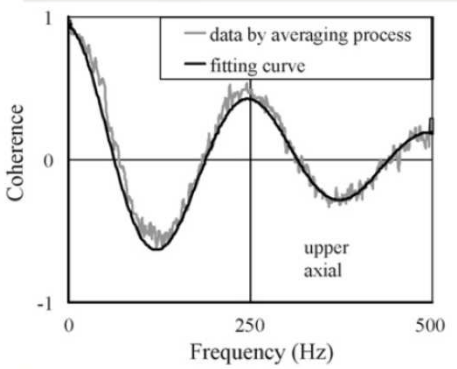
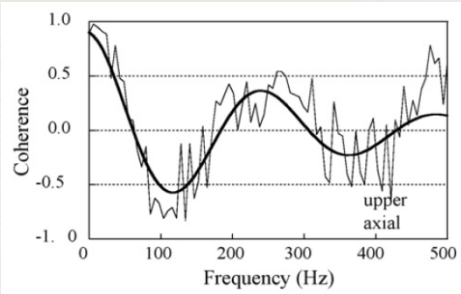
3. Applications

(1) Reactor vessel internals

- Japan (NUPEC) performed hydraulic flow tests with 1/5-scale model **to measure pressure fluctuations and flow-induced vibrations of the core barrel and the radial reflector**.
- The downcomer was modelled about 550,000 structured cells and three-dimensional transient turbulent flow was calculated using **LES**.







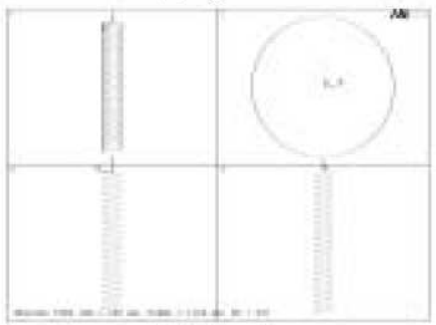
(b) compute

Fig. 2 Spectrums of pressure fluctuations

3. Applications (cont'd)

(2) Steam generator internals

- Flow induced vibrations in steam generator (SG) tubes of PWRs caused fretting, wear, and fatigue and finally lead to tube rupture.
- The thermal-hydraulic conditions of both tube side and shell side flow fields were analyzed using RANS methods built in CFX-5.7.
- ANSYS 7.0 was used to obtain the natural frequency and corresponding mode shape of the helically coiled tubes with various conditions.
- Predictions of turbulence-induced vibration, fluid-elastic instability and fretting-wear of the helically coiled tubes were made.



(e) Type E

Fig. 1. Finite Element Models of Helical Tube

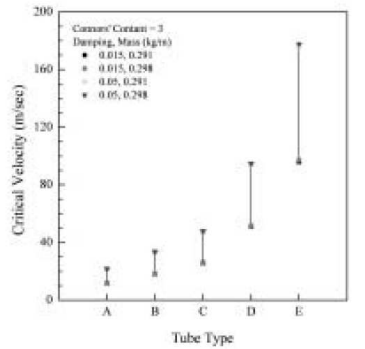


Fig. 10. Critical Velocity with Respect to Tube Type

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3. Applications (cont'd)

(3) Piping

- Thermal Fatigue Analysis of CANDU Feeder Pipe System for heatup and cool-down transient

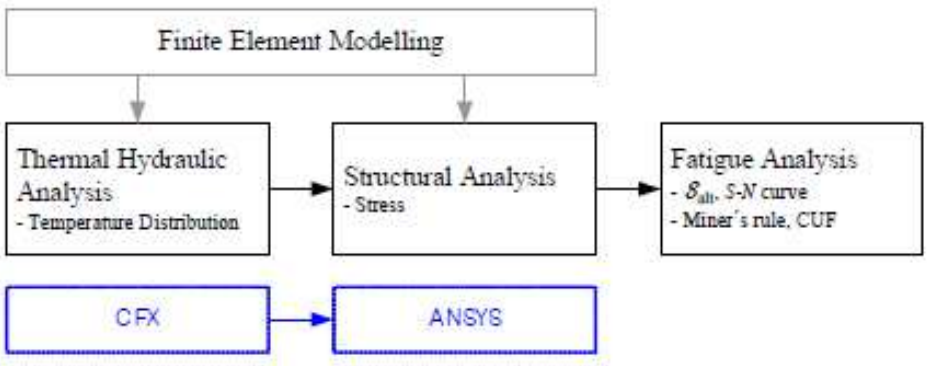
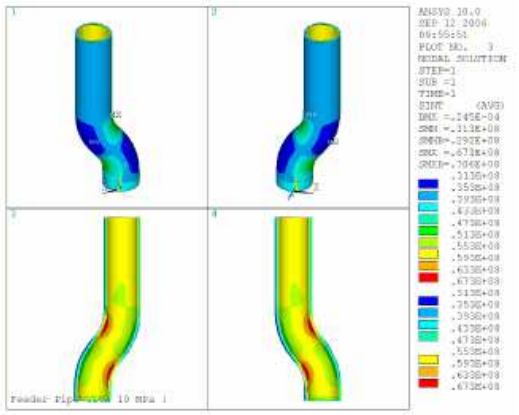


Figure 1. Procedure of FSI analysis.



(b) Stress intensity

Figure 2. Stress distribution for internal pressure.

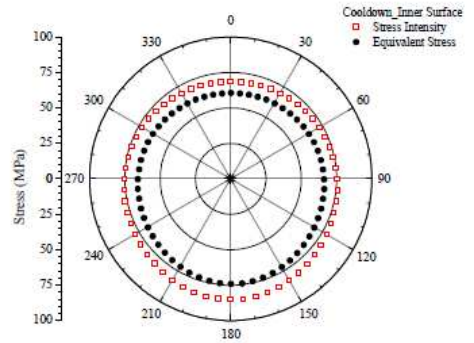
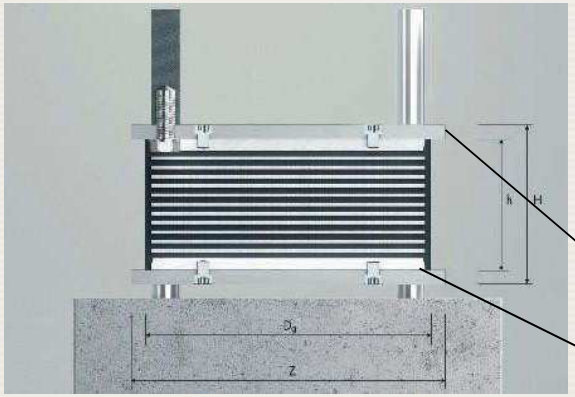


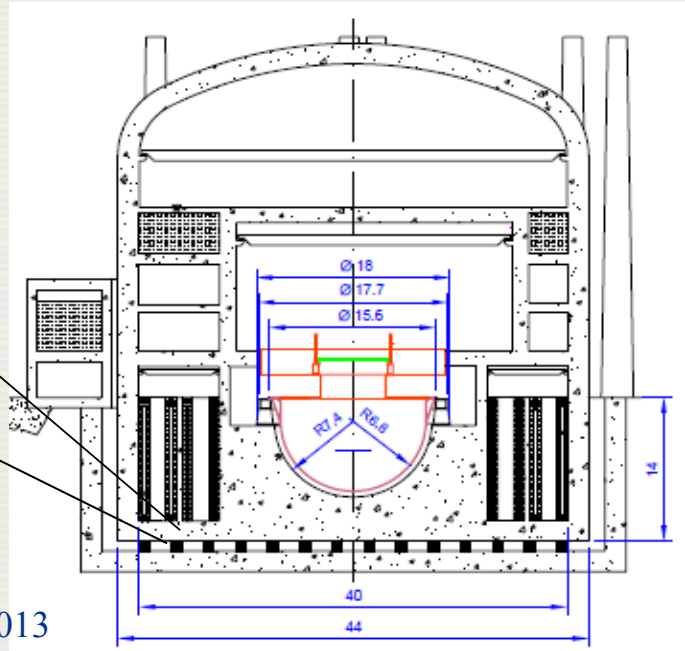
Figure 3. Stress variations along the circumference.

3. Applications (cont'd)

(5) NPP response in beyond design earthquake conditions

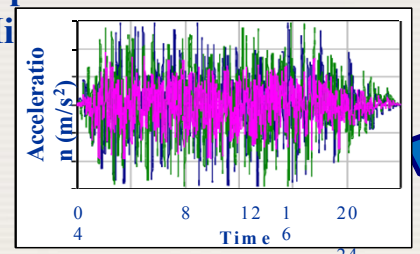
- The seismic behaviour analysis of a Liquid Metal Reactor was carried out in two step: the first one aimed at the evaluation of the propagation of the seismic accelerations through the isolated reactor building; the second one allowed to analyse the FSI effects induced by the fluid motion (seismically induced) in the RV and its main internal components.
- Earthquake induced loads at 90% lateral displacements consistent with 150% design level ground motion. Low natural frequency along the horizontal direction (f_i = 0.5 Hz).

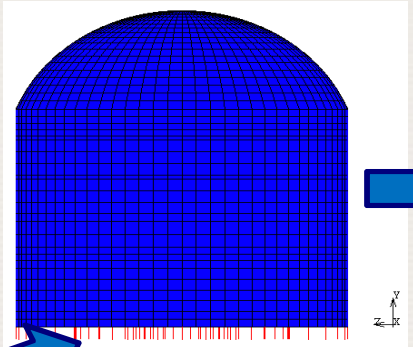


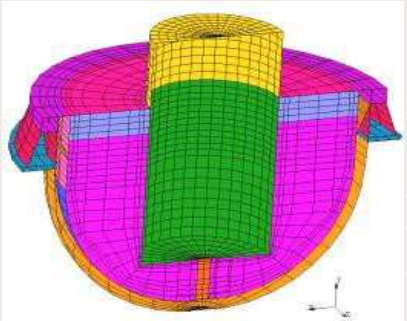


3. Applications (cont'd)

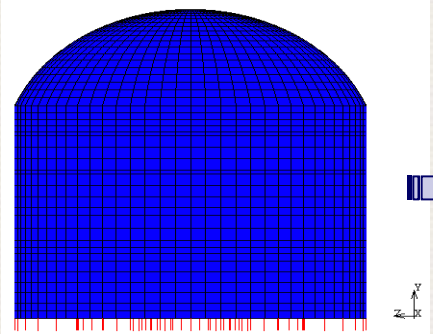
Input Acceleration Time Hi

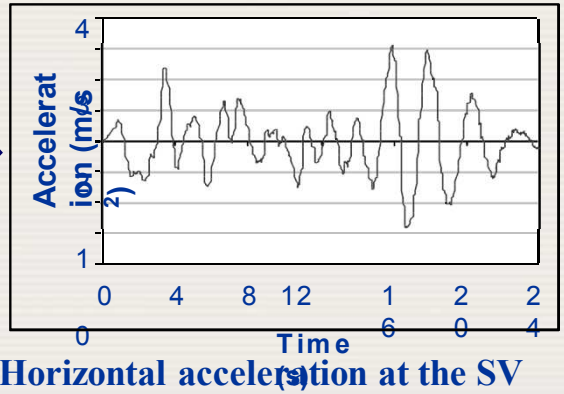






Reactor Building and RV preliminary models





Horizontal acceleration at the SV anchorage 14

- Components of the acceleration in the RB structure: **the reduction with respect to the input accelerations was about 40%. The vertical component, increases along the RB height.**

Closing Remarks

- **For the past three years, section 5 on** Computational Method for Fluid-Structure Interaction **has been producing draft guidelines.**
- Section 5 is still updating and will be **completed until end of 2014.**
- **It is welcome to hear ASME member's comments for further updating document**

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