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Predictive Study of CAP1400 Core Barrel Flow-induced Vibration-Part1: Turbulence induced Forcing Function

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ABSTRACT

CAP1400 is a 1400 MWe pressurized water reactor developed by SNERDI to be the next series of nuclear power plants in China. As a part of the feasibility study, a 1/6 scale model test of the pressure vessel and its internals was conducted to study the flow induced vibration (FIV) characteristics.

This paper describes the predictive study in calculating the core barrel vibration magnitudes and its successful comparison to the test measurements. It is noted that this is the first part, which describes the forcing function development and its successful comparison with the pressure pulsations measured from the scale model test, of a two-part series.

The structural aspects, i.e., the core barrel vibration predictive study and their comparison with the test results, will be described in the second part of this series.

1.0 Introduction

A core barrel, as its name implied, in a pressurized water reactor is a cylindrical barrel, containing the fuel assemblies inside, hanging from the vessel ledge. The impingement from the inlet flow and the ensuring turbulence generated by the flow turning and expanding at the bottom of the core barrel are the two major sources of core barrel vibration. Since core barrel is the major component of the reactor internals, the vibration of the core barrel has always been the number one concern for all reactor internal components.

The CAP1400 core barrel is an enlarged version of the AP1000 core barrel design with sizes similar to a traditional 4-loop plant. The major differences, from the traditional core barrel design, being a) there are no neutron panels attached b) there is a “even flow distributor”, shaped like a basket, attached to the bottom of the core barrel and c) there are four inlet nozzles with only two outlet nozzles. From past experience, the non-existence of the neutron panels would be very beneficial with respect to FIV. The other two differences are of minor effects.

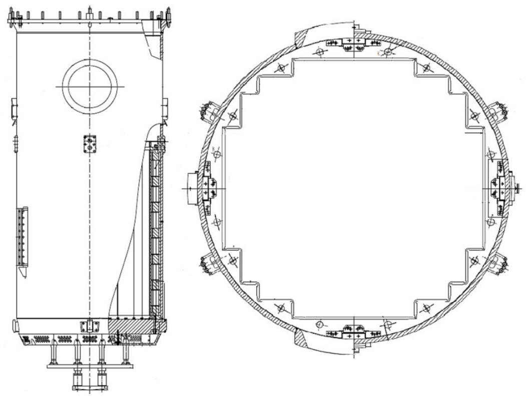

Figure 1-1 Illustration of CAP1400 Core Barrel

As a part of the CAP1400 feasibility study, a 1/6 scale model of the pressure vessel and internals was constructed and a FIV test was conducted in Chengdu, China, to study the flow induced vibration characteristics. Prior to the test, predictive studies were carried out on the various parts of the reactor internals. The overall objective of this paper, divided into Part 1 and Part 2, is to describe the methodologies used in predictive study of the core barrel vibration and the comparison with the test measurements. Part 1 is to describe the forcing function development and its successful comparison with the pressure pulsations measured from the scale model test. Part 2 will be on the prediction of the structural response of the core barrel vibration.

2.0 Overview

The entire project can be described in the following major parts

1) Benchmarking of the core barrel FIV response prediction methodology
2) Calculation of the CAP1400 scale model response
3) Comparison with the scale model test measurement

The overall flow chart is shown in Figure 1-2.

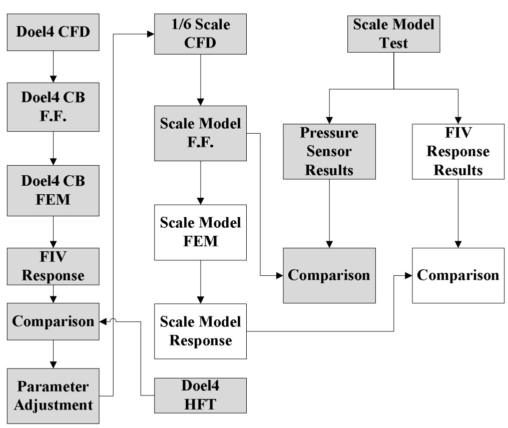

Figure 2-1 Overview of Prediction Study

Part 1 of this paper is shaded in gray and is more emphasized on the turbulence forcing function aspect of the subject. Part 2, while overlapping with Part 1 in the benchmarking process, is more focused on the structural aspect of the project.

2.1 Development of Turbulence Forcing Function

Because the coolant flow in the downcomer region is largely parallel to the axial direction, turbulence model of parallel flow over a large flat plate is deemed appropriate in this application. However, pressure pulsation over the entire core barrel outer surface is uneven; it is largely affected by the inlet and outlet nozzles in the circumferential direction and by the local structural disturbances in the axial direction. Therefore, for simplicity, the entire core barrel surface was evenly divided into 12 and 8 divisions in the circumferential and axial, respectively, directions, as shown in Figure 2-1. In other words, the entire core barrel surface is divided into 96 regions.

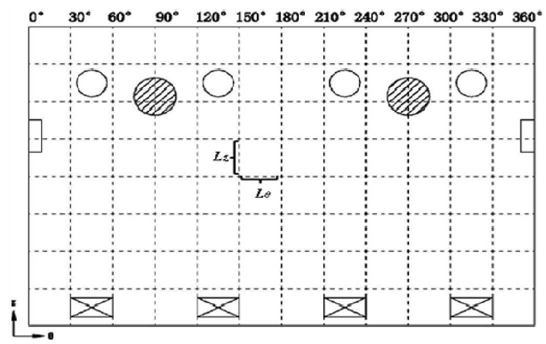

Figure 2-2 Division of Core Barrel Surface

Based on the divisions above, the turbulence forcing function, which is a function of both z and θ, on any given region can be expressed as [1],

$$G_p(x, f) = \left(\rho U^2\right)^2 \delta/U \ \phi\left(f^*, U, k\right) \tag{2-1}$$

Where

$G_p(x,f)$ ——Pressure PSD, Pa2/Hz;

x ——Any given division, function of z and □;

f ——Frequency, Hz;

ρ ——Density of coolant, kg/m3;

U ——Average flow velocity of a given region, m/s;

δ ——Downcomer width, m;

k ——kinetic energy, m2/s2

f * ——Reduced frequency $= f\delta/U$ (2-2)

$\phi\left(f^*, U, k\right)$ is a dimensionless parameter related to the turbulence level

Therefore, the pulsating pressure can be calculated based on Equation 2-1 . However, the correlation length in the downcomer region is in the order of the downcomer width which is substantially smaller than the dimensions of our divisions. Consequently, an equivalent pressure, which takes the correlation effect into consideration and will be assumed to be constant over a given region, can be derived based on the following expression, [1]:

$$G_f(x, f) = \iint \gamma(x', x'', f)\sqrt{G_p(x', f)\, G_p(x'', f)}\, dA' dA'' \tag{2-3}$$

Where is the coherence function and x' and x'' are any two points within a division. For a cylindrical surface, dA' and dA'' can be expressed as:

$$dA'dA'' = dz'\left(Rd\theta'\right)dz''\left(Rd\theta''\right) \tag{2-4}$$

Where R is the outside radius of the core barrel.

Based on [1], the coherence function, $\gamma\left(x', x'', f\right)$, can be decoupled in the circumferential and axial directions. In other words,

$$\gamma\left(x',x'',f\right) = \gamma_z\left(z',z'',f\right)\gamma_\theta\left(\theta',\theta'',f\right) \tag{2-5}$$

$$\gamma_z\left(z',z'',f\right) = e^{-\left(\frac{|z'-z''|}{\lambda_z}\right)} \tag{2-6}$$

$$\gamma_\theta\left(\theta',\theta'',f\right) = e^{-\left(\frac{R|\theta'-\theta''|}{\lambda_\theta}\right)} \tag{2-7}$$

Where, λ_z and λ_θ represent the correlation length, a function of frequency, in the axial and circumferential directions, respectively. From the experimental data of [2] and [3]:

Theoretically, the pressure on the surface could be different from one point to another. However, over the large surfaces of the core barrel, the variation in flow velocity, which is directly related to the fluctuating pressure, is relatively small. For this reason, we assume that within a given region, the amplitude of pressure is uniform. In other words, $G_p(x,f) = G_P(f)$. Consequently,

$$\sqrt{G_p\left(x',f\right)G_p\left(x'',f\right)} = G_p\left(f\right) \tag{2-8}$$

Substituting Equations (2-5), (2-6), (2-7) and (2-8) into Equation (2-3), we get:

$$\begin{aligned} G_f\left(f\right) &= G_p\left(f\right)\int_0^{L_z}\int_0^{L_z} e^{-\frac{|z'-z''|}{\lambda_z}} dz'dz'' \times R^2\int_0^{L_\theta}\int_0^{L_\theta} e^{-\frac{R|\theta'-\theta''|}{\lambda_\theta}} d\theta'd\theta'' \\ &= G_p\left(f\right)\Gamma_z\left(\lambda_z,L_z\right)\Gamma_\theta\left(\lambda_\theta,L_\theta\right) \end{aligned} \tag{2-9}$$

Where：

$$\Gamma_z\left(\lambda_z,L_z\right) = 2\lambda_z L_z\left[1-\frac{\lambda_z}{L_z}\left(1-e^{-\left(\frac{L_z}{\lambda_z}\right)}\right)\right] \tag{2-10}$$

$$\Gamma_\theta\left(\lambda_\theta,L_\theta\right) = 2\lambda_\theta L_\theta\left[1-\frac{\lambda_\theta}{L_\theta}\left(1-e^{-\left(\frac{L_\theta}{\lambda_\theta}\right)}\right)\right] \tag{2-11}$$

Thus, Equation (2-4) can be expressed as:

$$G_f(f) = \left(\rho U^2\right)^2 (\delta/U)\phi\left(f^*, U, k\right)\Gamma_z(\lambda_z, L_z)\Gamma_z(\lambda_z, L_z) \qquad (2\text{-}12)$$

Therefore, with the input of the local average flow velocity, U, and the kinetic energy, k, the PSD level at any given region can be calculated from Equation (2-12).

2.2 Benchmarking

The 1/6 scale model turbulence forcing function was generated first by benchmarking against the Doel 4 test data, [2]. The following steps were taken:
1.Build a Doel 4 core barrel-downcomer CFD model
2.Calculate Doel 4 PSD forcing function based on methodology used in [1]
3.Build a Doel 4 core barrel structural model, including the hydrodynamic mass effects and check against the Doel 4 core barrel frequency obtained from the hot functional test.
4.Perform a PSD analysis on the core barrel structural model using forcing functions derived in step 2)
5.Check against Doel 4 core barrel vibration magnitude and adjust parameters used in the forcing function, if necessary.
6.Build a 1/6 scale CAP1400 core barrel-downcomer CFD model
7.Using the parameters developed from the benchmarking process to generate the corresponding scale model forcing functions. It is noted that the scale model test was done in room temperature.

2.3 Doel 4 CFD Model

Doel 4 is a Westinghouse designed 3xL plant and is also the reference design for the Westinghouse AP1000 series of reactor internals. The hot functional test, which was focused on the lower internal vibration, was conducted in 1985. It is noted that Doel 4 is a neutron panel plant.

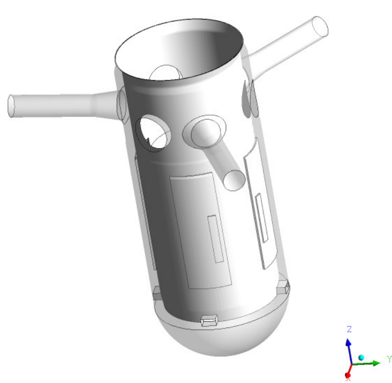

Figure 2-3 Doel4 CFD model

The Doel4 CFD model is shown in Figure 2-2. In this model, other than the downcomer and the lower head regions, the contours of the attachments such as the neutron panels, the specimen baskets, the radial keys and corresponding clevis inserts are also included. The inlet nozzles were extended in sufficient length to make sure the flow field is fully developed. Because our focus is in the downcomer region, the flow field of the down-stream components, such as the lower support plate, the lower core plate and the fuel assemblies are not modeled in details. The parameters used in the Doel4 CFD model, along with those used in the scale model CFD, are compared as follows:

Table 2-1 Comparison of Doel4 and Scale Model CFD Parameters [2]

Parameter	Unit	Doel 4	1/6 Scale
Coolant Temperature	℃	297	25
Coolant Density	kg/m^3	733	998
Dynamic Viscosity	kg/(m·s)	8.9E-5	8.9E-4
System Pressure	MPa	15.5	1.2
Inlet Velocity	m/s	21.4	22.8
Inlet Nozzle ID	mm	698	108

The realizable κ–ε option of the ANSYS Fluent Code was used for the CFD analysis. The results are shown in Figure 2-4 thru 2-5.

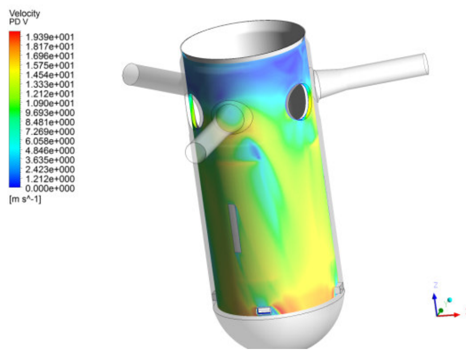

Figure 2-4 Doel 4 Downcomer Flow Velocity

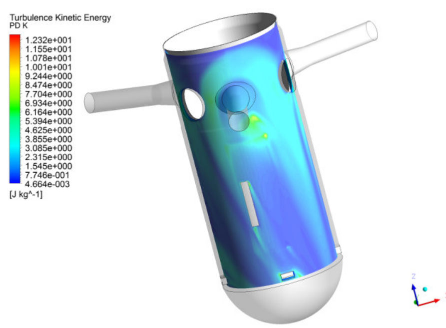

Figure 2-5 Doel 4 Downcomer Kinetic Energy

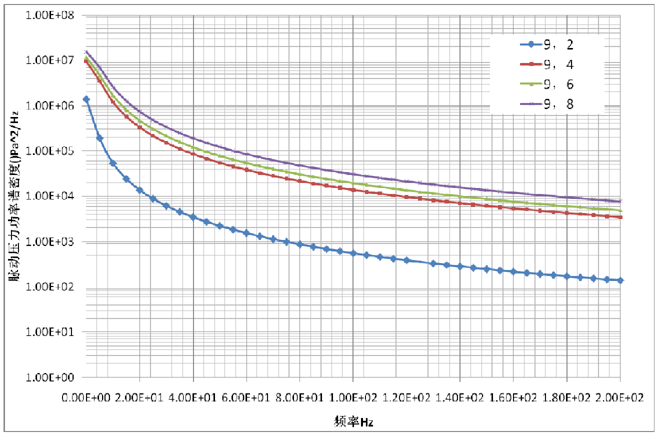

Figure 2-6 Doel 4 Pressure PSD on Core Barrel Outer Surfaces at Several Elevations

The pressure PSD was subsequently applied to a Doel 4 core barrel model and the amplitude of the core barrel was calculated. The calculated amplitude was within 4% of the actual measurement. This part of the study will be presented in more details in Part 2 of this series.

2.4 Scale Model CFD Model

The 1/6 scale model to be is a scaled replica of the CAP1400 design except
a) The upper head and the upper head internals, i.e., the upper guide tube and the IGA were not modeled
b) The various gaps between the internal components are not scaled.
c) The fuel assemblies were represented by a simplified structure having the same dead weight
d) The core shroud structure was somewhat simplified to allow the installation of transducer wirings.

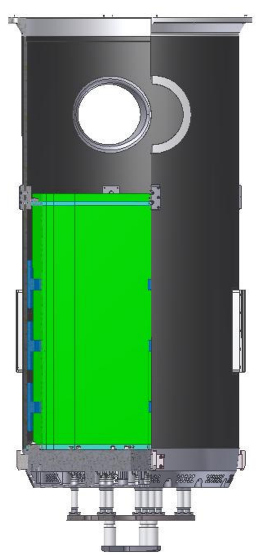

Figure 2-7 Scale Model Test Configuration
The 1/6 scale lower internal CFD model was constructed with the same methodology except
a) All contour of the secondary support assemblies were modeled
b) All flow holes in the lower core support plate were explicitly modeled and
c) The fuel assemblies were represented by a porous volume having the same pressure drop of the representative fuel assemblies.

Since the CAP1400 core barrel is largely a symmetrical structure, only 1/4 model is needed.

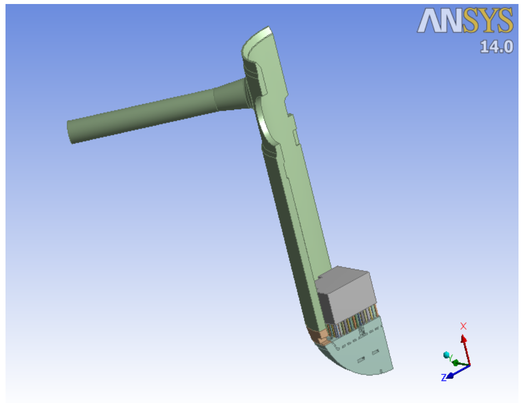

Figure 2-8 CAP1400 1/6 Scale CFD Model

The corresponding CFD results are shown in the following figures

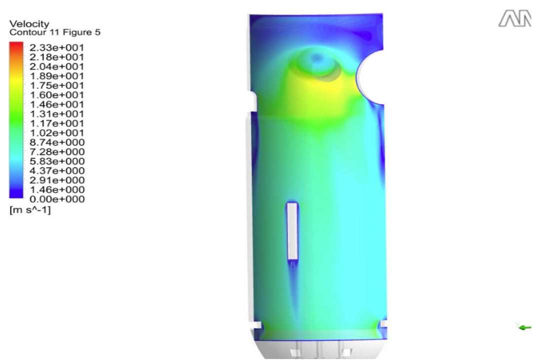

Figure 2-9 Scale Model Flow Velocity Distribution

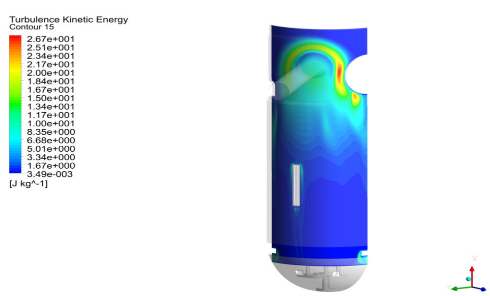

Figure 2-10 Scale Model Kinetic Energy Distribution

3.0 Scale Model FIV Test

As mentioned above, the 1/6 scale model FIV test was conducted in Chengdu, China. There are four loops used in this test where each pump can deliver a maximum flow rate of 816m3/hr. In this test, a total of 11 pressure transducers were installed, on various angles and elevations, measured from the top of the core barrel flange, on the core barrel outer surfaces.

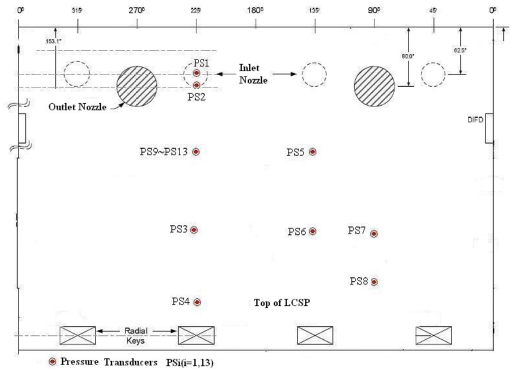

Figure 3-1 Scale Model Pressure Gage Arrangement

Figure 3-2 Pressure Transducers #9 thru #13

Outside the pressure gages, there were a total of 6 strain gages installed on both the inside and the outside surfaces of the core barrel under the core barrel flange. In addition, there were two accelerometers and two relative displacement transducers (LVDT) installed at the bottom of the core barrel. The test was conducted in room temperature and pressure.

3.1 Scale Model Test Results

Of the 13 pages, gages #2 and #3 malfunctioned. The rms pressure measured from the rest of the gages are compared with the calculated values as follows:

Table 3-1 Comparison of Calculated and Measured (rms) Pressure (kPa)

#	Transducer Locations	Test/ Calculated
1	Inlet Nozzle	1.60
4	225° - 1300 mm	0.73
5	135° - 600 mm	0.90
6	135° - 900 mm	0.98
7	90° - 912 mm	1.48
8	90° - 1104 mm	1.34
9	225 ° - 600mm	0.90

10		0.98
11		0.97
12		0.97
13		0.98

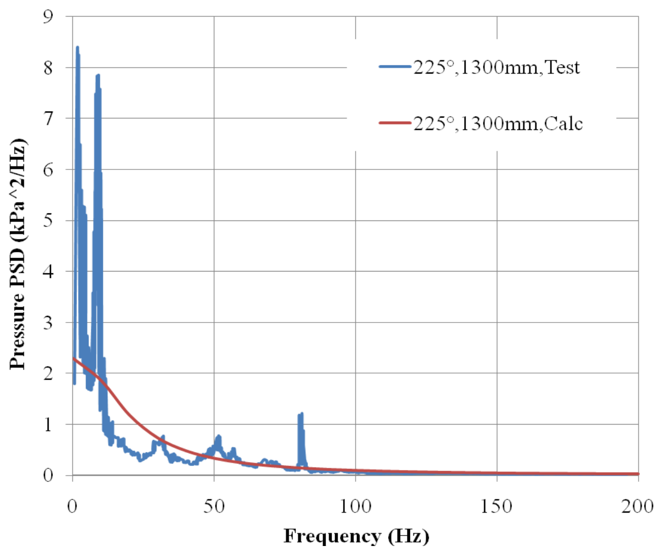

Figure 3-3 Comparison of Measured and Calculated Pressure Spectra

It is seen that other than the around 10 Hz content, most likely a system acoustic mode, and the around 83 Hz spike, which is the pump frequency, the rest of the measured pressure spectra matches pretty good with the calculated spectra. Along with the good match in the core barrel vibratory amplitudes, which will be presented in Phase 2 of this paper, we conclude that the proposed turbulence forcing function has successfully accomplished the prediction work.

4.0 CONCLUSION

This paper combined the CAP1400 scale model CFD results along with the empirical forcing functions and the correlation effect, synthesized by Westinghouse, to postulate a set of forcing functions acting on the core barrel outer surfaces. The results, in terms of fluctuating pressures, are compared fairly well with the measured pressures from the scale model test and, thus, demonstrating the validity of the proposed methodology.

5.0 REFERENCES

[1] M.K. Au-Yang, "Flow-Induced Vibration of Power and Process Plant Components," ASME Press (2001): Pg. 230-235.
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