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Fluid–structure interaction modelling of a PWR fuel assembly subjected to axial flow

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ABSTRACT

Nuclear industry needs tools to design reactor cores in case of earthquake. A fluid–structure model simulating the response of the core to a seismic excitation has been developed. Full scale tests considering one fuel assembly are performed to identify coefficients (added mass and damping) that will be used as inputs in the models. Tests showed that the axial water flow induced an added stiffness. In the paper, an expression of the model accounting for the fluid in the fuel assembly with a porous media model and in the by-passes with a leakage flow model is developed. Numerical simulations are compared to experiments and showed good agreement.

1. Introduction

Earthquakes can irreversibly damage nuclear power plants especially in the core, where the nuclear fuel assemblies containing enriched uranium dioxide have to be particularly resistant. Before building a nuclear power plant, it is necessary to make sure that the core will resist the worst possible earthquake conditions liable to occur at the reactor site. Therefore, safety measures are required to insure the drop of control rods and that the core is cooled when the fuel assembly spacer grids strike each other during seismic excitation of a Pressurized Water Reactors (PWR). A way to insure these two criteria is to prevent the spacer grids from buckling. Engineers need special tools for designing and maintaining reactor cores. The tools usually used involve structural modelling accounting for mass and damping coefficients induced by fluid–structure interactions. These coefficients are identified on full scale test results, they are of major concern since the fuel assembly response and thus the grids integrity will directly depend on them.

The reactor core made of fuel assemblies is subjected to an axial water flow to cool the reactor. The flow strongly modifies the dynamical behaviour of the fuel assemblies (Tanaka et al., 1988; Hotta et al., 1990; Collard et al., 2004), therefore the identification of the fluid forces is important to provide a relevant modelling of the fuel assemblies behaviour. The first approximation of the fluid forces is to consider them as added mass and damping (Rigaudeau, 1997; Viallet et al., 2003). A more complex expression of these fluid forces is given by Païdoussis (2003) in which the velocity and the relative direction of the flow with respect to the fuel assembly are accounted for. Ricciardi et al. (2009a,b) proposed a porous media approach based on the Païdoussis theory.

In previous study (Ricciardi and Boccaccio, 2012), tests dedicated to the identification of the fluid forces acting on a full scale fuel assembly were performed. These tests highlighted an added stiffness effect under axial flow. This phenomenon was first observed in Ricciardi et al. (2010) and then discussed in Ricciardi and Boccaccio (2012). Identified coefficients of

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stiffness, damping and mass showed a strong dependency on the lateral by-passes. These by-passes are necessary to allow the displacement of the fuel assembly. Further tests involving fluid measurements in the by-passes (Ricciardi and Boccaccio, 2014b) showed that fluid velocity fluctuations were induced by the fuel assembly displacement. A delay was observed between the displacement and the fluid fluctuations. The delay decreases with the increase of the axial velocity, thus the phenomenon involved is related to the fluid convection. A first attempt to model the added stiffness was made by Ricciardi and Boccaccio (2015) based on Bernoulli equation and an artificial delay. In this paper a model accounting for the flow in the fuel assembly and in the by-passes is proposed.

2. Experimental apparatus

HERMES T is a single phase hydraulic loop that can handle full scale PWR 1300 MW fuel assemblies. The pump can supply 1200 m^3/h in axial flow and 400 m^3/h in cross-flow, at 35 bar and 170 °C. Therefore, the flow rate is similar to the PWR conditions, the lower temperature (PWR operates at 315 °C) allows to provide accurate measurement devices to the test-section. In the present study, only axial flow is considered at 50 °C.

The fuel assembly used is made up of 25 guide tubes and 264 fuel rods, each having a height of 4.5 m and linear density of about 200 kg/m. The guide tubes are welded to a top and a bottom nozzles at their boundaries. The fuel assembly is clamped to the test-section at the top and the bottom. The bottom nozzle is placed on the lower core plate which presents four injection tubes. The upper core plate presents a square hole. Both lower and upper core plates are bolted to tubes to tranquilize the flow (Fig. 2). The test-section is about 40 mm larger than the fuel assembly in the excitation direction and 10 mm larger in the orthogonal direction. Grids of the fuel assembly are around 200 mm wide. Grids and nozzles induce singularities in the flow since they locally modify the extruded rod bundle geometry and thus the hydraulic diameter and the flow distribution. The displacement of the fifth grid is imposed with a hydraulic jack (Fig. 1). The force applied by the hydraulic jack is measured by a load cell. An acrylic window allows making optical fluid measurements with a Laser Doppler Velocimetry (LDV) device. The displacements of the 2nd to the 9th grid are measured with Linear Variable Differential Transformer (LVDT) sensors. The movable portion of each sensor is a stainless steel rod with a diameter of 2.5 mm and is placed across the right by-pass.

Static and dynamic tests are carried out. For static tests, the axial fluid velocity is measured at three altitudes in the fuel assembly and in the by-passes (Fig. 3), namely, between grids 2 and 3, between grids 4 and 5 and between grids 8 and 9. For each altitude, measurements are made every 2 mm along a line in the $\mathbf{e_z}$ direction in each by-pass, and 6 lines in the fuel assembly, homogeneously distributed (Fig. 4). Static tests are performed with the fuel assembly at rest, and with a 10 mm imposed displacement of the fifth grid toward right by-pass. An earthquake shows a frequency range between 0 and 10 Hz and the first natural frequency of a fuel assembly is between 1 and 2 Hz. During an earthquake most of the vibration energy is captured by the first natural mode of the fuel assembly so that this study is focused on the first mode and the excitation frequency range includes the first natural frequency. For dynamic tests, a swept sine ranging from 0 to 3 Hz (Fig. 5) with an amplitude of 6 mm is imposed. Tests are performed under axial flow for three axial velocities (1.5 m/s, 3 m/s and 5 m/s,

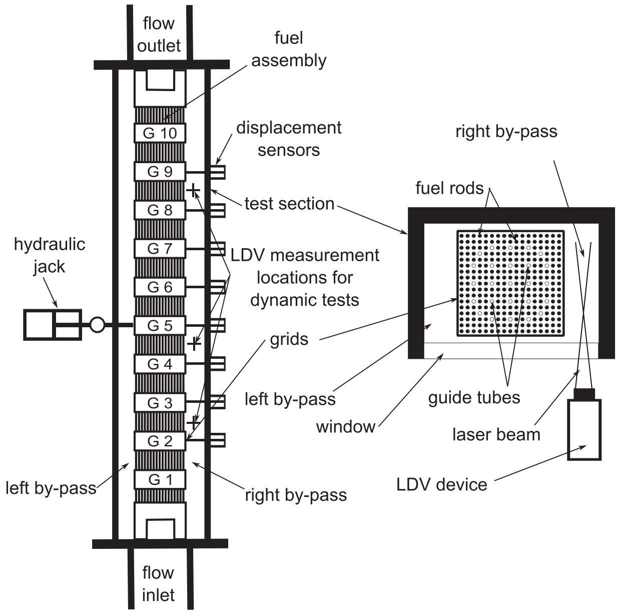

Fig. 1. Experimental apparatus.