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Operational modal analysis of flow-induced vibration of nuclear fuel rods in a turbulent axial flow

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HIGHLIGHTS

- We describe an analysis technique to evaluate nuclear fuel pins.
- We test a single fuel pin mockup subjected to turbulent axial flow.
- Our analysis is based on operational modal analysis (OMA).
- The accuracy and precision of our method is higher compared to traditional methods.
- We demonstrate the possible onset of a fluid-elastic instability.

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ABSTRACT

Flow-induced vibration of nuclear reactor fuel pins can result in mechanical noise and lead to failure of the reactor's fuel assembly. This problem can be exacerbated in the new generation of liquid heavy metal fast reactors that use a much denser and more viscous coolant in the reactor core. An investigation of the flow-induced vibration in these particular conditions is therefore essential. In this paper, we describe an analysis technique to evaluate flow-induced vibration of nuclear reactor fuel pins subjected to a turbulent axial flow of heavy metal. We deal with a single fuel pin mockup designed for the lead–bismuth eutectic (LBE) cooled MYRRHA reactor which is subjected to similar flow conditions as in the reactor core. Our analysis is based on operational modal analysis (OMA) techniques. We show that the accuracy and precision of our OMA technique is higher compared to traditional methods and that it allows evaluating the evolution of modal parameters in operational conditions. We also demonstrate the possible onset of a fluid-elastic instability by tracking the modal parameters with increasing flow velocity.

1. Introduction

Investigating flow-induced vibration of reactor components such as fuel rods is essential in view of ensuring safe operation of nuclear plants (Pettigrew et al., 1998). In order to understand and to assess the possible safety hazards due to flow-induced vibration of the fuel rods in realistic operating conditions of the reactor, we propose a method based on operational modal analysis (OMA) techniques to analyze those vibrations (Fu and He, 2001; Guillaume et al., 2003; Ewins, 2000). To illustrate the potential of our method we have measured the response of a single fuel rod in a dedicated experimental setup and we show that our technique yields higher precision and accuracy than traditional direct or spectrum based methods. By increasing the flow velocity we were able to create similar turbulence conditions as in the actual lead–bismuth eutectic (LBE) cooled MYRRHA reactor (De Bruyn et al., 2011; Aït Abderrahim et al., 2012). We estimated the modal parameters for each flow condition and we compared those in order to assess the actual effect on the fuel pin. The high precision and accuracy of our method allows for a reliable and unbiased modal identification of the MYRRHA fuel assembly. This identification can then be compared with the design specifications in order to draw conclusions about safety.

Since our method can be applied in operational environments, i.e. without need for any other excitation, features can be revealed that would go undetected otherwise such as the onset of an instability as discussed in Section 4.3.

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Nomenclature

d	channel diameter
f_0	fundamental frequency
ξ	damping ratio
ψ	mode shape
D	fuel pin diameter
Re	Reynolds number
U	flow speed
U/Df_0	reduced velocity
d_h	hydraulic diameter
C_m	dynamic amplification factor
m_f	mass of displaced fluid

The remainder of this paper is structured as follows. We proceed in the next section (Section 2) with a discussion of the experimental facility and of the used materials and measurement techniques. The section explains the experimental setup as well as the supports and construction of the fuel rod. Section 3 then briefly introduces the theoretical models and vibration analysis techniques. We then devote a section to the vibrational analysis of the fuel rod using data from a laser Doppler vibrometer (LDV) system. The vibrational analysis includes four major parts. The first part is an estimation of the reduced amplitude as a function of the flow velocity to situate the problem in the field of flow-induced vibration, followed by a discussion of the operational modal analysis techniques used to identify individual vibrational modes of the rod. The (critical) damping and the added mass of the fuel rod are the subjects of the last two parts.

2. Materials and measurement techniques

We have manufactured fuel rod mockups from stainless steel cylindrical tubes with a diameter of 6 mm and a length of 1400 mm (Fig. 2). We chose these dimensions to mimic those of the actual rods that will be used during operation of MYRRHA, the nuclear reactor specifically targeted in our research. The cylindrical tubes were filled with a piece of solid lead–bismuth (5) supported by hollow PVC spacers (3) (Fig. 2). A spring (6) was inserted to simulate pressure applied to the lead–bismuth. Once filled the hollow tube was sealed with dedicated tips. These tips fix the rods in the fuel assembly with a slit and key mechanism and hence they determine the boundary conditions of the system.

To produce similar flow conditions as in the reactor we have constructed a dedicated water loop as shown in Fig. 1. The fuel pins were installed in that experimental set-up and their vibrations were monitored using two LDV systems. We have shown in De Pauw et al. (2013, 2012) that the LDV technique yields a superior measurement signal-to-noise ratio for this application.

3. Theoretical background and analysis methods

3.1. Flow-induced vibration correlation

The fuel rods in the MYRRHA reactor will experience a nominal flow of approximately 2 m/s of LBE at 300°C along the axial direction from bottom to top (i.e. left to right in Fig. 2). Such flow conditions yield a turbulent regime and can excite flow-induced vibrations (FIV) of the fuel rods and of the entire sub-assembly as a whole. Since we have axial flow and turbulence as the main excitation mechanism we can use the simulation criterion established by Burgreen (Prakash et al., 2011). This criterion allows calculating the required flow speed and temperature of any fluid, e.g. water, to simulate the same flow conditions (and thus vibration amplitudes) as those that one would obtain using LBE. In terms of the velocity ratio, that criterion becomes,

$$\frac{U_w}{U_{\mathrm{LBE}}} = \frac{\rho_{\mathrm{LBE}}^{0.5}}{\rho_w^{0.5}} \frac{\mu_{\mathrm{LBE}}^{-0.33}}{\mu_w^{-0.33}} \frac{E_{\mathrm{warm}}^{-0.33}}{E_{\mathrm{exp}}^{-0.33}} \frac{M_{\mathrm{warm}}^{0.165}}{M_{\mathrm{exp}}^{0.165}} \quad (1)$$

where U_w is the water flow speed and U_{LBE} is the LBE flow speed. At a given temperature, ρ_{LBE} and ρ_w are the respective densities while μ_{LBE} and μ_w are the dynamic viscosities. Finally $E_{\mathrm{warm}}/E_{\mathrm{exp}}$ and $M_{\mathrm{warm}}/M_{\mathrm{exp}}$ are the ratios at reactor operation ('warm') and test temperature ('exp') of the Young moduli and the mass per unit length, respectively. The values for the Burgreen ratios that apply to our tests are summarized in Fig. 3.

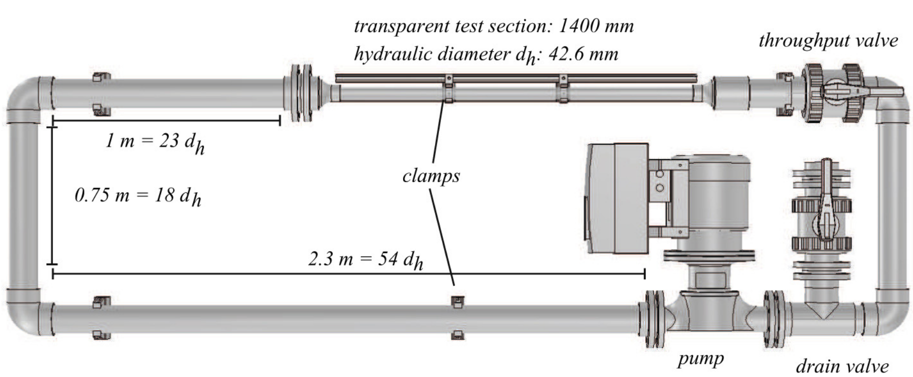

Fig. 1. Concept drawing of the test facility.

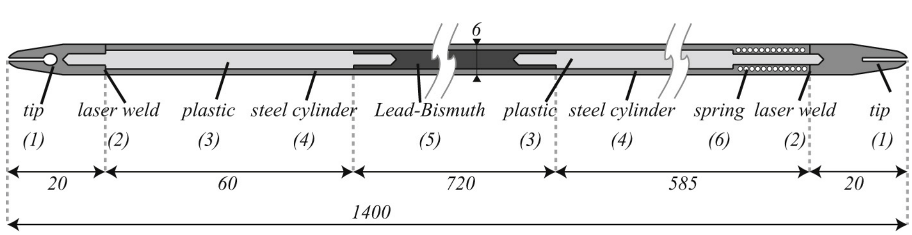

Fig. 2. Design of constructed fuel pin mock-up.