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Axial-flow-induced vibration experiments on cantilevered rods for nuclear reactor applications

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ABSTRACT

Axial-flow-induced vibration has been experimentally investigated with clamped-free cantilevered cylindrical rods confined in a tube and subjected to axial water flow directed from the rod free-end towards the clamped end: a simplified configuration relevant for water-cooled nuclear reactor cores. Non-contact optical techniques have been used to simultaneously detect the rods vibration and the flow field around the vibrating rods free-end. The source of excitation is turbulent buffeting at low flow velocity, while a movement induced excitation component is present at large flow velocities. The rods flow-induced vibration consists of a fuzzy period-1 motion: a periodic (period-1) motion with a chaotic component that increases in relative importance as the flow velocity is increased. The experimental data provided here are particularly suited for numerical fluid-structure model development and benchmarking, as they combine a rich fluid-structure multi-physics interaction with a relatively simple configuration and include both the flow field and the mechanical response of the vibrating rods.

1. Introduction

Structural vibrations induced by axial flow in slender cylindrical structures are generally of small amplitude, and therefore of little concern in most practical applications. Notable exceptions are nuclear reactor cores and other systems composed of closely-spaced cylindrical elements exposed to axial flows. Even small amplitude vibrations can consequently result in impacting between adjacent cylinders or between cylindrical elements and supports, thus causing fretting wear, fatigue and eventually structural cracking and system failure. Fretting wear is in fact responsible for the majority of fuel leaks observed in water-cooled nuclear reactors. This highlights the importance of analyzing and predicting axial-flow-induced vibrations for the safe and profitable operation of nuclear power stations. In most cases of practical interest involving cylindrical structures in axial flow, the observed flow-induced vibrations are so-called *subcritical vibrations*: low-amplitude vibrations whose dominant frequency corresponds to the first mode of the cylinder (Païdoussis, 2014). Divergence and flutter have been observed but are generally of little practical concern, as the flow velocities required for the inception of divergence and flutter are much higher than those typical of most engineering applications. With subcritical vibrations, the source of excitation is typically turbulent buffeting, so that these flow-induced vibration problems are characterized as Extraneously-Induced Excitations (EIE), as turbulence is largely independent of the movement of the structure, or of the way the structure affects the flow field. Turbulence in the flow induces pressure fluctuations along the cylinder surface that are spatially and temporally not uniform, thus giving rise to a random lateral load on the cylinder surface that causes lateral motion and triggers the vibration. These pressure fluctuations are typically wide-band, so that the cylinder can extract energy from the flow at frequencies corresponding to its natural frequencies, with the first natural frequency typically being dominant.

In nuclear fuel bundles, and similarly with other systems composed of closely spaced cylindrical elements, even small-amplitude vibrations can appreciably change the geometry of the flow passage and therefore affect the axial flow, thus adding a Movement-Induced source of Excitation (MIE) to the flow-induced vibration problem. The proximity of the fuel rods, and the relatively high density of the coolants used in nuclear applications, result in strong fluid coupling among different fuel rods, meaning that the vibration of one rod can propagate to the adjacent rods as well. Therefore, in nuclear reactor fuel bundles, as the fuel rods extract energy from the turbulent flow and vibrate, their movement affects the axial flow and adjacent rods influence each other through fluid coupling. These interactions result in a tightly coupled

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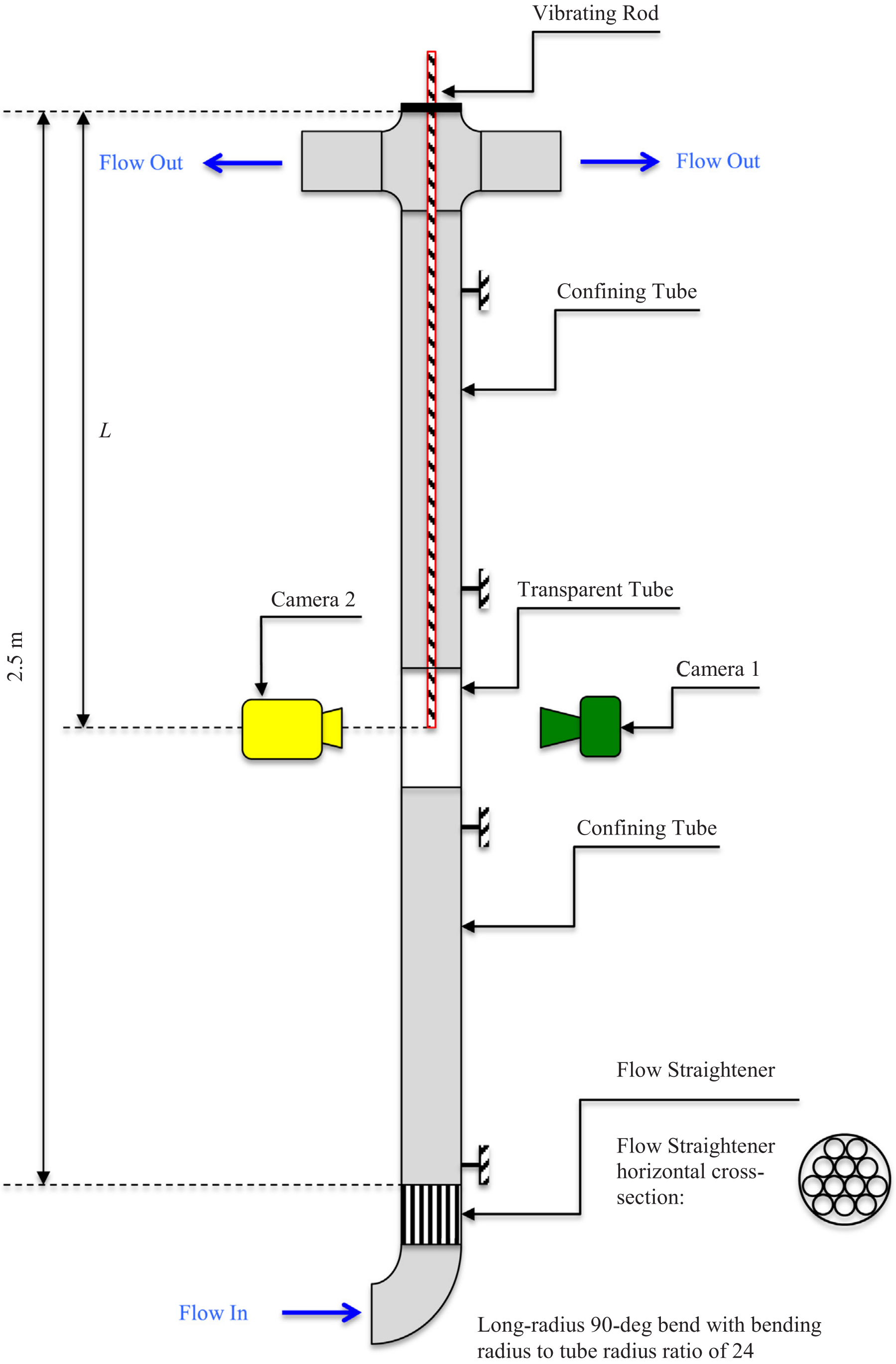

Fig. 1. Schematic representation of the test piece.

multi-body fluid-structure interaction problem, where the axial flow and the rod vibrations dynamically interact and affect each other. Secondary sources of rod excitation that add further complexity to these problems include: 1) far-field disturbances transmitted through the flow, such as pump noise and cavitation; 2) vibrational noise transmitted through the system support structures; 3) inlet conditions in the fuel assemblies and flow restructuring based on the design of the lower core support plate, debris bottom nozzle filters and lower plenum internals; 4) variation in distance among different fuel assemblies due to positioning; and 5) fuel rod bowing and side effects near the core edges.

Axial-flow-induced vibrations in nuclear reactor applications are currently investigated using coupled computational fluid dynamics (CFD) and structural dynamics (SD) simulations, as analytical modeling and purely experimental investigation alone are not feasible. Analytical modeling of axial-flow-induced vibrations is, in fact, hampered by the procurement of the detailed information needed as input to the models: fluctuating pressure fields are very difficult to characterize a priori, and far-field upstream effects are problem-specific and very challenging to incorporate. On the other hand, testing at prototypical nuclear reactor operating conditions is too expensive to rely on a purely experimental