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Non-linear vibrations of nuclear fuel rods

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ABSTRACT

Single zirconium alloy nuclear fuel rods with clamped-clamped boundary conditions and subjected to harmonic excitation at various force levels were experimentally studied. Different configurations were implemented, and the fuel rods were tested in air and submerged in quiescent water. Moreover, the effect of the contained fuel pellets was also reproduced by representative metallic pellets inside the rods. Non-linear stiffness and damping parameters were extracted from experimental vibration response curves by means of a specifically-developed identification tool. For the cases where the fuel pellets were removed or axially compressed, it was found that the axial-symmetry of the fuel rod resulted in a pronounced one-to-one internal resonance. The internal motion of the fuel pellets is a source of friction and impacts during vibrations, thus complicating further the linear and non-linear dynamic behavior of the system. A very significant increase of the viscous modal damping with the vibration amplitude was observed during geometrically non-linear vibrations, which is particularly relevant and in advantage of safety.

1. Introduction

Clusters of cylindrical arrays subjected to external flow, with axial and cross flow components, are common in the power generation (Chen, 1985; Païdoussis, 2006; Weaver et al., 2000) and aerospace component manufacturing (Lepore, 1991) industries. In most cases these arrays are designed to minimize the fluid-structure interaction induced by the flowing fluid to avoid large amplitude array instabilities. Nevertheless, flow-induced vibrations of cylindrical arrays remain a significant performance and safety concern in the power generation industry. Past studies (Païdoussis et al., 2011) have estimated that the cumulative damages for the power industry over a decade, due to fluid-elastic instabilities of cylindrical arrays, are close to one billion US dollars. A recent example of flow-induced vibration failure in the power generation industry is the premature failure of the San Onofre nuclear plant steam generators that ultimately cost approximately three to four billion US dollars at the utility ratepayers' expense.

In nuclear plants, fuel assemblies are used in the reactor core to provide the fuel for the generation of power. In pressurized water reactors (PWR), a fuel assembly is defined by the United States Nuclear Regulatory Commission (US NRC) to be a structured group of fuel rods which are long, slender, zirconium metal tube(s) containing pellets of fissionable material, which provide fuel for nuclear reactors. Spacer grids are utilized to bundle the fuel rods in a square configuration to form a fuel assembly. Fuel assemblies and fuel rods, in classical PWR square, hexagonal or CANDU type cores, are subjected to flowing water and are susceptible to large fluid-structure oscillation amplitudes (Bhattacharya, 2013; Dragunov et al., 2013; Païdoussis, 2006). In addition, seismic and loss-of-coolant accident conditions generate *external* excitations that could induce undesired complex fuel assembly component oscillations. Thus, flow-induced vibration remains a significant component failure mechanism for nuclear reactors and is related to plant safety and operating plant costs. In addition, tubes used in steam generators undergo similar types of complex excitations and suffer from similar types of flow-induced instabilities (Yuan et al., 2017). Even though flow-induced vibrations have been studied extensively and empirical formulations are available for use in the nuclear industry, questions related to the underlying mechanisms for the onset of rod instability (*e.g.,* flow-induced damping, internal resonances, effect of pellets, and so on) when subjected to complex boundary conditions, flow conditions and external excitations remain unanswered.

Previous studies in the literature have investigated numerically the fluid coupled vibrations of fuel bundles (Chen, 1975; Païdoussis and Curling, 1985) as well as flow induced vibrations of fuel rods and heat

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exchanger tubes (Au-Yang and Burgess, 2007; De Santis and Shams, 2017; Hofstede et al., 2017; Kang et al., 2001; Kim and Kim, 2005; Liu et al., 2012, 2017; Sandström, 1987; Simoneau et al., 2011). A detailed finite-element analysis of the behavior of fuel rods supported by spacer grids in quiescent water and a comparison with experiments can be found in (Choi et al., 2004). Furthermore, flow-induced vibrations of a single mockup fuel rod were measured by (De Pauw et al., 2015). Fuel rod non-linear vibrations are also related to fretting wear due to contact with the spacer grids and may lead to fuel leaks; the impact of fluid-induced vibration and of the gap during operation between rods and grids were investigated numerically (Bakosi et al., 2013; Hu et al., 2016; Kim, 2010).

Non-linear parameter identification of the coupled systems is difficult but important. A number of approaches to develop numerical tools for the identification of non-linear parameters that play significant role in large amplitude oscillations are described in Adams et al. (1998). Furthermore, the work by Bennett et al. (1997) cites a number of challenges for specific identification tools designed to extract experimental fluid-elastic forces. Ahikari and Woodhouse (2001a,b) in a two-series study developed theoretical models identifying viscous and non-viscous damping parameters based on experimental results for modes and frequencies of a system. A more recent development to identify the non-linear parameters of large fuel rod vibrations is the work by Alijani et al. (2016); Amabili et al. (2016a,b); and Delannoy et al. (2015). The tools developed in the last three studies help the designer in identifying useful dynamic parameters that describe the large-amplitude vibrations reached by structures, at their resonant frequencies, during experiments and possibly during operation. The work in these recent papers consisted of reference experiments on simple geometries with and without fluid-structure interaction and the development of simplified numerical tools and methods for the identification of non-linear vibration parameters of vibrating structures. More complex cases involving internal resonances - the non-linear interactions between different vibration modes at one resonant frequency - were also considered (Delannoy et al., 2016).

In the present study, a number of dedicated vibration experiments and subsequent identification of critical system parameters were performed on zirconium alloy nuclear fuel rods provided by Framatome in order to characterize the non-linear behavior of nuclear core elements. Single fuel rods were subjected to clamped-clamped boundary conditions and to linear and geometrically non-linear vibrations in absence and in presence of quiescent surrounding fluid. Flowing fluid conditions, clusters of tubes and spacer grids were excluded by the present investigation but will be featured in upcoming studies.

The large amplitude vibration of a single fuel rod under harmonic excitation in a small frequency range around a resonant frequency can be described by a single degree-of-freedom (DOF) modified Duffing oscillator (Amabili, 2008). The 1-DOF oscillator can model a wide variety of non-linear vibration phenomena such as non-linear jumps in vibration amplitude, hysteresis cycles and several types of instability leading to chaos. Geometrical non-linearities are taken into account by the modified Duffing equation and the presence of internal resonances can be taken into account by a model with two degrees of freedom. The vibration amplitude for such an oscillator undergoing forced external harmonic excitation is controlled by damping around resonance. The evolution of damping of a fuel assembly in flowing water has been studied in the past (Viallet and Kestens, 2003) indicating a non-linear relationship between reduced damping coefficient and the first eigenfrequency of the fuel assembly for different oscillatory amplitudes and irradiation conditions. For fuel rods, the weak nonlinearity of the hydrodynamic damping with respect to fluid flow velocity is described in Connors et al. (1982) and an empirical formulation to describe damping is established. Additional studies (Hassan et al., 2011) investigated the effect of damping on triggering multi-span tube instabilities using time domain modeling for tube arrays. Finally, experimental and theoretical studies on flow-induced fuel assembly and fuel rod damping highlighted the non-linear response of the fuel assembly and fuel rod for higher flow conditions and different types of external excitation (Brenneman and Shah, 2000; Collard et al., 2004; Fardeau et al., 1997;). Modeling of the damping parameters for flow-induced vibrations was investigated by Vandiver (2012) who recommended the definition of a dimensionless damping parameter for cylinders experiencing flow-induced vibration. It is well understood that damping in the non-linear regime can be described by several models; for instance, an innovative non-linear damping model is discussed in recent papers by Amabili (2018b) and Balasubramanian et al. (2018). A traditional modal damping ratio, based on viscous dissipation, was retained in the current study. Its value has to be adjusted according to the vibration amplitude in order to capture the experimental results. This is a clear indication that damping and stiffness are both non-linear. While the presence of geometrically non-linear stiffness is well known, the presence of a strong increase of damping with the vibration amplitude is still not established in the literature on non-linear dynamics. Since the vibration amplitude in the non-linear regime is not proportional to the excitation amplitude, the current study conducted stepped-sine experiments at several constant force amplitude levels, thus implying the identification of one damping ratio per force amplitude level. In previous studies it had been shown that, for sufficiently large excitation levels, damping increases with the amplitude of the response in plates and panels (Alijani et al. 2016; Amabili & Carra, 2012; Amabili et al., 2016a,b) and in water-filled circular cylinders (Delannoy et al., 2016; Amabili et al., 2016a,b). The present research shows that damping increases for fuel rods as well, which constitutes an obvious safety design advantage.

The presence of one-to-one internal resonances in axisymmetric structures significantly complicates the damping behavior as the increasing energy of large amplitude vibrations is not only dissipated through non-linear damping but also transferred from the main vibration mode (*driven mode*) to the non-linearly coupled mode (*companion mode*). Since the distribution of kinetic energy between two modes reduces the maximum amplitude reached by the vibration of each mode, this phenomenon may correspond to a reduction of the severity of the oscillation.

Uranium pellets, normally present inside fuel rods during operation with a spring-operated system to keep the pellets compressed during operation, were included as mechanically equivalent inert metal pellets, which were inserted inside the rods. A compression system was implemented to reduce the axial play of the pellets. Pellets are supposed to introduce two strongly non-linear mechanisms – dry friction and shocks – while they move with respect to each other and shake against the fuel rod walls. These phenomena were not modeled mathematically in the present work, although their effect on the non-linear vibrations of the system under test was studied experimentally as they manifested themselves during laboratory testing. In general, modeling the effect of pellets on the stability of the fuel rod system is rather difficult (Park et al., 2009), but it could be approximated by comparing the natural frequencies from modal test results of the rod with pellets against the rod without pellets. Impacts and dry friction constitute, ultimately, non-linear mechanisms of energy dissipation. Therefore, their effect on vibration is captured by the non-linear dependence of the equivalent modal damping parameter on vibration amplitude. It has to be noted, however, that the motion of the pellets constitutes an additional “internal” (in the sense that it is not visible outside the tube but describes vibrations happening inside it) degree of freedom of the physical system, which is modelled less accurately by the 1-DOF Duffing equation.

2. Experimental setup

Several hollow zirconium rods were sourced and employed for experiments. These rods are identical to the ones used in fuel assemblies of pressurized water reactors. However, they are made shorter and are