Progress in Nuclear Energy 107 (2018) 193–204

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

A comprehensive dynamic model for analysing the vibrational behaviour of a CANDU fuel string

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ARTICLE INFO

Keywords:
CANDU fuel string
Vibrations
Non-linear systems
Friction and contact
Linear complementarity problem

ABSTRACT

Inside a pressure tube, under a large drag load induced by the coolant flow, CANDU fuel bundles form a coherent structure called fuel string. The presence of a large number of unilateral frictional contact (UFC) constraints makes the dynamic behaviour of the fuel string very complex and highly nonlinear. In this paper, a comprehensive dynamic model for handling a large number of UFC constraints is presented. The complex fuel string problem is formulated to be a Linear Complementarity Problem (LCP). Use of the LCP eliminates the need for iteration and satisfies all the UFC constraints in the whole fuel string simultaneously. The computational power available these days allowed us to handle all the constraints among fuel rods, between rods and pressure tube and between neighbouring bundles. Finite element method was employed in order to discretize the fuel rods and endplates. The systems of equations of motion were then discretized in the time domain using Bozzak-Newmark integration scheme. This numerical model can be used to find the dynamic response of a fuel string to any given excitation including unsteady fluid forces or acoustic pressure pulsations. In this study, the response of a 12-bundle fuel string to gravity and harmonic excitations was found; all frictional contact forces everywhere along the string are obtained and can be used to predict fretting and material loss. The numerical model presented in this study can be used to improve new fuel designs, mitigate and decrease damage, develop new safety standards and handle other engineering problems where large numbers of UFC's is a challenge, like other types of nuclear fuel rods and heat exchanger tubes.

1. Introduction

A CANDU reactor core consists of a few hundred horizontal fuel channels. As it is illustrated in Fig. 1, a string of 12 or 13 fuel bundles is placed inside the pressure tube of each fuel channel. During operation, heavy water coolant enters into the pressure tube at the inlet, passes through all fuel bundles, and removes the heat generated by each fuel element. The last fuel bundle at the outlet end is supported by the side stop or shield plug that hold the fuel string against the hydraulic drag caused by the coolant flow. The coolant that flows inside the pressure tube is highly turbulent and produces unsteady drag, side, and lift forces that act on every fuel bundle. In reactor measurements showed that fuel bundles vibrate during operations ((Misra et al., 1994)-(Judah, 1992)). Flow-induced vibration of fuel bundles has caused moderate to severe wear on the inner surface of the pressure tube and on the surface of bearing pads and spacer pads inside a CANDU nuclear reactor ((Misra et al., 1994)- (Judah, 1992)). Moreover, vibration has caused and continues to cause an undesirable amount of debris in the coolant, and even loss of bundle integrity due to cracking of the endplates (Misra et al., 1994).

Lau et al. (1992) reported that a mass flow rate of 34 kg/s in a channel with 13 bundles caused a drag force of 691 N per bundle. Flow-induced drag couples the behaviour of individual fuel bundles together through contact and friction and forms the fuel string. Modeling the vibration of the fuel string inside a pressure tube is an extremely challenging problem. UFC constraint is one of the main challenges. Unilateral frictional contact refers to the constraint between two contacting bodies in which there is no penetration in the normal direction and the generalized Coulomb's law is applicable to slip/stick in the tangential direction(s). In a CANDU fuel string there is a large number of UFC constraints to be handled, between the fuel elements and pressure tube, between the neighbouring fuel elements and between neighbouring bundles. The most challenging nature of UFC is that the constraining forces vary with the displacements or velocities in a non-smooth manner spatially and with time. Moreover the direction and magnitude of friction and contact forces are not known a priori.

To quantify vibration of a fuel string in a pressure tube, a dynamic model is needed to account for all the potential contact constraints in

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https://doi.org/10.1016/j.pnucene.2018.04.007
Received 3 September 2016; Received in revised form 23 June 2017; Accepted 9 April 2018

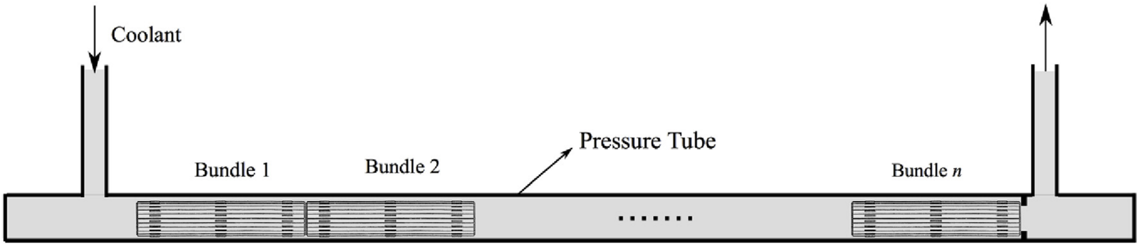

Fig. 1. A CANDU fuel string consisting of n bundles.

the system. A literature review revealed that up to date there is no such a comprehensive dynamic model for the fuel string. However contacts between two beams, or contact of a single beam with another rigid body have been discussed in many studies. Hild (2000) employed global and local finite element approximations and a Lagrange multiplier method for handling unilateral contact between two independently discretized bodies. Litewka and Wriggers (2002) analyzed the frictionless contact between two three-dimensional beams of rectangular cross sections. They have used a contact search algorithm to determine an active set of contact and presented the penalty and Lagrange multiplier formulations. Xu et al. (2008) have employed complementarity formulation to handle frictionless contact in a static problem involving an array of beams inside a tube with rigid boundaries. Yetisir and Fisher (1997) did some numerical simulations to predict the material loss and fretting wear between the bearing pads of a single fuel rod and pressure tubes due to turbulence flow. They also performed measurements to validate their work and concluded that the small-scale turbulence in a parallel flow is not enough to cause the wear observed in CANDU reactors. Hassan and Rogers (2005) investigated vibration of a single fuel rod subjected to turbulence excitations. They have applied several frictional models to understand the effect of tube-support clearance and preload on the predicted work rate. Work by Hassan and Rogers (2005), later on was improved by Mohany and Hassan (2013) to consider 3 locations of contact between the fuel rod and the pressure tube and to account for the effect of contact from neighbouring fuel rods.

Frictional sliding between contacting surfaces is known to dissipate energy and cause damage in many engineering systems, including fretting of the pressure tube in a fuel channel. For a vibrational system, the beginning and end of each state (stiction or slip) cannot be known a priori. Although for some very simple vibration systems, it may be possible to determine the precise moment of occurrence of each state, it is difficult to obtain a solution on an individual basis without a systematic approach for a large-scale dynamical system with hundreds or thousands of UFC constraints such as the fuel string vibration.

It is imperative that the method to be used be fast and robust for each time step. As is pointed out by Hassan and Rogers (2005), if a contact procedure/algorithm requires exhaustive search and iterations to achieve a solution of acceptable accuracy at one time step, such an approach may not be feasible in studying the vibrational behaviour of a large-scale problem. In this paper, a numerical methodology is developed to obtain solutions for dynamical systems with a large number of UFC constraints. Auxiliary incremental displacement variables are defined and through variable transformations, the complex problem reduced to a linear complementarity problem. Then the LCP are solved using the Lemke algorithm. Friction between the bundles and pressure tube through bearing pads and between neighbouring bundles is two-dimensional. In this study, the direction of the frictional force is determined the same way as it was done by Fadaee and Yu (2015). Fuel rods and endplates are discretized in the spatial domain by means of the finite element method. An implicit incremental displacement Bozzak-Newmark scheme is then employed to seek a numerical solution in the time domain. Velocity based implicit time-integration schemes are superior to the displacement-based schemes when only frictional constraints are present in a dynamical system. On the other hand, displacement-based schemes are preferred when contact constraints associated with the opening and closing of gaps between or among components are present. When both frictional and unilateral contact constraints must be considered, an incremental displacement based scheme is superior. In addition, changes in configurations of fuel string due to power variations and pressure tube ageing are also best formulated by the incremental displacements.

2. Description of the dynamical system

Fig. 1 illustrates n CANDU-6 fuel bundles laid horizontally inside a pressure tube. Under the hydraulic drag induced by the coolant flow, individual fuel bundles form a structure called the fuel string. Coupled with large-scale contact constraints between different components, the so-formed fuel string can exhibit very complex dynamic behaviours under fluid flow excitation. A CANDU-6 fuel bundle consists of 37 fuel rods and two endplates. As is shows in Fig. 2, the radial and circumferential gaps between neighbouring fuel elements are designed and maintained by means of spacer pads for eliminating direct sheath-to-sheath contact and wear and to avoid localized hot spots. Bearing pads are introduced to the outer ring fuel elements at three or more bundle cross-sections to prevent direct contact between sheath and pressure tube (see Fig. 2 and Fig. 3). A 37-element endplate, made of Zircaloy, consists of three concentric circular rings to hold the fuel elements at their designed positions (see Fig. 3).

A CANDU fuel rod contains a number of cylindrical UO_2 pellets inside a thin hollow Zircaloy sheath. The sheath-to-pellet interaction can vary depending on the life stage of the fuel. However with the collapsibility of the sheath and sufficient pellet-sheath interfacial pressure, the pellets and sheath form an integral compound beam-like structure (Tayal (1989)) with a large length-to-diameter ratio (about 40). In this study we assumed that pellet and sheath are fully stick together and form a monolithic composite beam.

It is known that in reality fuel bundle components are not manufactured perfectly, i.e. endplates are not perfectly flat and sheaths are not perfectly straight. Not only that, these geometrical properties of bundle components changes as fuel reaches different stages of its life. In this study, fresh fuel bundles are considered, and it is assumed that endplates are perfectly flat and sheaths are perfectly straight. All solid components are discretized in the space domain by means of the finite element method. A three-node higher-order mixed beam finite element (Yu and Fadaee (2012)) is used for modeling of fuel rods as straight compound beams for coupled bending-axial and bending-torsional vibration. A special nine-node thick plate finite element (Yu and Fadaee (2016)) is employed for the in-plane and out-of-plane deformations of endplates. The finite element discretization of solid components yields a large number of DOF's for a fuel string. Since only a small percentage of the total DOF's is involved in the UFC formulations, the component substructure method (Bathe (1997)) is used to eliminate the interior DOF's and significantly reduce the dimensions of the non-smooth dynamical problem.

The equation of motion for a single fuel rod may be written as

$$[m]\{\ddot{q}\} + [c]\{\dot{q}\} + [k]\{q\} = \{Q\}_{i+1} + \{Q_f\} - \{Q_c\} + \{R_{ep-fe}\} \tag{1}$$