Fuel Rod Flow-Induced Vibration Overview

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1. Introduction

To ensure fuel design safety and structural integrity requires the response prediction of fuel rod to reactor-coolant flow excitation. However, there are many obstacles in predicting the response as described in Fig.1. Even if the response can be predicted, the design criteria on wear failure, including correlation with the vibration, may be difficult to establish because of a variety of related parameters, such as material, surface condition and environmental factors. Thus, a prototype test for each new fuel assembly design, i.e. a long-term endurance test, is performed for design validation with respect to flow-induced vibration (FIV) and wear. There are still needs of theoretical prediction methods for the response and anticipated failure. This paper revisits the general aspect on the response prediction, mathematical description, analysis procedure and wear correlation aspect of fuel rod's FIV.

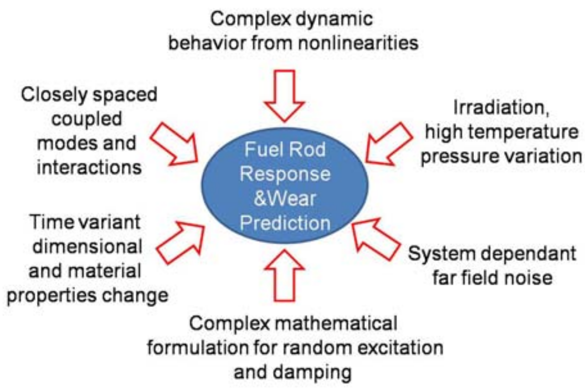

Fig. 1 Obstacles of response prediction for fuel rod.

2. General Aspect

FIV of fuel rod subjected to an axial coolant flow in the operating reactor core is a random and subcritical vibration. Thus, fluid-elastic instability is not matter because of much lower operating flow velocity compared to the critical velocity. In subcritical vibration, excitation and damping mechanisms are crucial factors to determine system dynamics and vibration response. Fluctuating pressure under turbulent boundary layer is primary excitation source of which dominant spectral energy is concentrated in relatively low frequency range of 50 Hz. Both near and far-field noises including pump noise and flow disturbances from upstream components are broad band and random in nature and lead fuel rod to vibrate narrow banded and randomly.

Fuel rod vibration become a "design problem" only if the vibration amplitude is large to lose function of cladding or to result material damage, such as cladding worn-out and leakage of radioactive material into coolant. Thus there is a need to find such conditions on the point of vibration and wear to be a problem beforehand.

3. Mathematical Description

Linear dynamic equation of motion applicable to the fuel rod vibration can be described by a simple matrix form as *eq.* (1)[1]. The original equation was derived by Paidoussis[2] in 1970 for the slender cylindrical body in uniform axial flow, with twin limitations of flow and plane vibration.

$$[M]\ddot{y}+[C]\dot{y}+[K]y=[F] \quad (1)$$

where y is the fuel rod's lateral displacement,
$M=M_r+M_a$ (M_r: structural mass, M_a: added-mass)
$C=C_s+C_v+C_f$ (C_s: structural damping, C_v: viscous damping, C_f : flow dependent damping)
$K=K_s+K_f+K_c$ (K_s: structural stiffness, K_f: fluid-elastic stiffness, K_c: grid support contact stiffness)
$F=F_q+F_w+F_t+F_o$ (F_q: steady fluid force, F_w: wake forces, F_t: turbulence force, F_o: other than fluid forces)

Dynamic stability of fuel rod can be studied with zero excitation force (F=0) in *eq.* (1). With tracking the sign and the value of complex eigenvalues, the type of instability and critical velocity can be identified in linear scheme. However, response prediction requires full descriptions of excitation force term, F.

Added-mass (M_a) due to surrounding fluid is active only for dense fluid and reduce the system natural frequency a little. Proximity of rods in fuel bundle increases added-mass effect. Fluid/structure couplings by added-mass cause k rod-bundle to have $2k$ cross sectional modes of vibration and each groups of coupled frequency corresponds to the associated axial bending mode.

Damping is a crucial factor for determining fuel rod vibration. Structural damping includes energy loss due to rubbing (sliding) or impacting at the intermediate grid support. Viscous damping is associated with viscous drag forces acting on the fuel rod and opposes the lateral velocity of the rod. The viscous damping (force) is a function of Stokes number and increases with decreasing Stokes number and bundle spacing. Some experimental and theoretical results show that damping increases with increasing flow velocity.

Damping is identified by only measurement with range of 0.02~0.15 for equivalent damping. Corilois effect from rod's free end shape can influence damping[3,4].

Fluid elastic stiffness means fluid force proportional to rod displacement. Thus it is effective at very high flow velocity. But reactor operating environmental condition may increase or decrease fuel rod response frequency according to the reactor burnup or elapsed time. K_c is commonly modeled by linear springs.

Prediction of subcritical vibration response requires characterization of force terms. Steady fluid force and wake force is not important for axial FIV. But, periodic frequencies in wake flow can cause fuel rod mechanical resonances. Additionally, support or spacer grid is responsible for wake flows that can contribute as a additional excitation source, primarily by increasing the turbulence level in the flow downstream.

Solution of random vibration problems requires a model of cross spectral density of random pressure force. It is widely accepted that a coherence function (of random fluctuating pressure) can be factorized into a stream-wise and a cross-stream component, and that each factor can be represented by the two parameters: the convective velocity and correlation length which can be known from experimental correlations or scale model testing. But, all these parameters to formulate random pressure force are difficult to measure. Fuel rods usually respond to low frequency excitation of the pressure fluctuations. Widely-used pressure fluctuation spectrum has two distinct regimes: dominant power in low frequency is flat over the certain frequency range, but low-power in high frequency rapidly decrease with increase of frequency. Assumptions of homogeneous pressure field must be doubted because the spacer grids and mixing devices generate upstream disturbance and increase in the turbulence level. However, the homogeneousness in pressure field can be still applied to predict the averaged rod response without gross loss of accuracy.

4. Analysis Procedure

A scope of FIV analysis, to predict fuel response and wear, consists of: i) flow distribution calculation (or measurement), ii) dynamic parameter evaluations, iii) formulating of the random pressure fluctuation, iv) vibration response calculation, and v) resulting damage assessment for comparison. The FIV problem at small number of critical fuel pin in specific area (i.e. high neutron flux and suspicious high cross flow region) in the reactor core[5]. Thus, a flow analysis is required to obtain local flow condition in the fuel flow channel and reactor. Parameters to be calculated include flow velocity, turbulence intensity, major damping factors, effective tube mass, dynamic stiffness, flexural rigidities and natural frequencies, etc. Formulating pressure force is to build a relation between the power spectral density (PSD) function of fluctuating pressure in fuel subchannel and the reduced frequency from the literature test data or by direct measurement. The vibration response is then calculated by probabilistic structural dynamic analysis using the acceptance integral concept. The eq. (2) is the simplest form of equation and often used to estimate the mean square vibration response of structure excited by flow turbulence.

$$E[y^2(x)] = \sum A G_p(f_\alpha)\psi_\alpha^{\,2}(x) J_{\alpha\alpha}(f_\alpha)/\{64\pi^3 m^2 f_\alpha^{\,3}\zeta_\alpha\} \quad (2)$$

where $J_{\alpha\alpha}$ is joint acceptance, A is the surface area or length, G_p is random pressure PSD.

5. Summary

This paper introduces the general aspect of response prediction, mathematical descriptions and analysis procedure of fuel rod's FIV. It is widely accepted that fuel rod vibration and wear is not a problem for normal operation and normal support condition. To get meaningful results from theoretical analysis and research, there is a need to find the critical support conditions to wear out the cladding tube or to result material damage on the cladding such that the fuel vibration become a "design problem". This is an essential pre-step for materialize FIV-wear correlations.

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