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Fluid Damping Variation of a Slender Rod in Axial Flow Field

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1. Introduction

PWR fuels are subjected to the flowing coolant during the reactor operation. Since the fluid density is greater than that of air, the dynamic behavior in the coolant condition is absolutely different from that in the air. Especially the energy dissipation mechanism, damping, is much more active, thus a lot of potential energy cannot be transferred to the kinetic energy or vice versa. The flow induced damping is beneficial to fuel integrity in that impact energy due to severe accidents such as earthquake dissipates rapidly. A nuclear fuel bundle is composed of many slender fuel rods which contain fission material. The slender rod is typical structure in the fuel, therefore fluid damping estimation on the rod should be an important clue leading to fuel bundle damping identification. Severe accidents could cause fuel assembly vibration in the core, but large motion could be damped out rapidly when a strong damping mechanism is involved. This study proposed an analytic damping model considering the axial flow condition. In addition, the specific damping values with respect to the flow speeds are calculated.

2. Mechanical Model and Numerical Evaluations

Slender beam model subjected to axial coolant flow is introduced, and the fluid damping is estimated with the model.

2.1 Fluid force over the Structure

When a structure is exposed to axial flow dominant environment, two kinds of fluid force excite the structure. One is friction force in the vertical direction, and the other is drag force in the horizontal direction. When the structure moves laterally, the horizontal friction component can also be activated. The friction force , τ, can be written in the following equation[1].

$$\tau = \frac{f}{8}\rho_w V^2 \tag{1}$$

In Eq.(1), f denotes friction coefficient which can be found from Moody's chart[1]. ρ_w and V denote flowing water density and the axial flow velocity. The other force, drag force(σ), can be expressed as

$$\sigma = 0.5 C_d \rho_w (V - \dot{u})^2, \tag{2}$$

where C_d and $\dot{u}$ denote drag force coefficient and the slender structure lateral velocity. It is assumed that the structure vertical motion is negligible to that of the lateral motion. Therefore such relative velocity can only be seen in Eq.(2). The other external forces including random force do not contribute to energy dissipation, thus this study will not discuss the other external forces.

2.2 Structure Model Subjected to Flowing Water

Park et al.[2] showed that unstable motion in the fuels rarely can be seen, since the fuel rod flexibility is relatively stronger. Based on the previous work and with Eq.(1), (2), One can derive mathematical formulation in the lateral direction as

$$\begin{aligned} & m_c \ddot{u} + 2 m_f V \frac{\partial \dot{u}}{\partial x} + \mu_L \dot{u} + m_f V^2 \frac{\partial^2 u}{\partial x^2} + \mu_L V \frac{\partial u}{\partial x} \\ & + EI \frac{\partial^4 u}{\partial x^4} = p(x,t), \end{aligned} \tag{3}$$

where m_f is fluid mass per unit length and m_c is combined unit mass of the structure and flow. u denotes the lateral motion, and x is axial coordinate. μ_L is the combination of τ_L and σ_L which mean lateral component of the frictional force and drag force. In addition, E and I denote elastic modulus and the second area moment. It is noted that the single term in the right hand side of Eq.(3) is an external force. The second term is a Coriolis force induced from the relative structure motion to the axial flow, and it contribute to additional damping. The third term in Eq.(3) is linearized in the lateral direction. The fourth term is centrifugal force and it can be seen in a beam with compressive force. Increasing the fourth term reaches to negative stiffness, but the fifth term contributes to positive stiffness. One can see the first and the last term commonly in the normal beam with uniform cross section properties.

2.3 Simulation Results

The above equation cannot be solved directly. Usually one can estimate the solution using Galerkin method[3]. Introducing a comparison function that satisfies all boundary conditions, the solution can be approximated as in Eq.(4)

$$u \approx \sum \psi_k(x) q_k(t) \tag{4}$$

Where, $\psi(x)$ and $q(t)$ denote a comparison function and generalized coordinate. Multiplying a weighting function to Eq.(3), and integrating over the domain after inserting Eq.(4) into Eq.(3) lead to Eq.(5)

$$M\ddot{\bar{q}} + Z\dot{\bar{q}} + K\bar{q} = F \qquad (5)$$

Where, M , Z and K denote mass, damping, and stiffness matrix. $\bar{q}$ and F mean generalized coordinate vector and the external force vector, respectively.

Characteristic equation from Eq.(5) produces complex roots representing dampings and natural frequencies of the system. For example, Fig. 1 shows variation of the first mode damping and the corresponding natural frequency as a function of axial flow velocity. Since the smallest mode is easily excited during earthquake accidents, the first mode damping is critical to the seismic performance. Noting that the usual axial flow velocity is around 5 m/s, one can see that the damping in the normal condition is approximately 45%. That is damping increases as the axial flow velocity becomes large. On the other hand, natural frequency is decreasing at the very low velocity and increasing again. The other damping values, from the second to the fourth modes, are delineated in Fig. 2. They are also increased as a function of the speed. When the initially deflected structure is released suddenly, the motion is dependent on the axial flow speed as can be seen in Fig. 3.

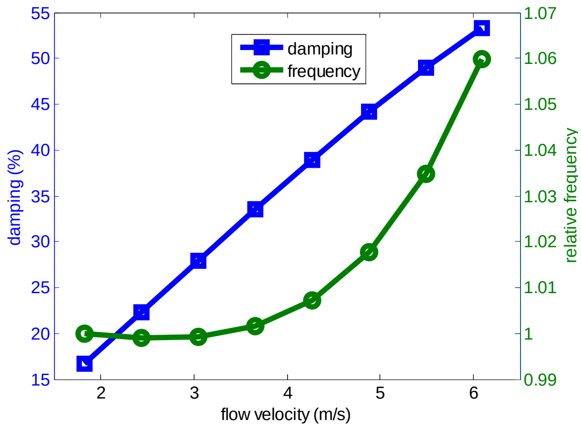

Fig. 1. The first mode damping(square solid) and the natural frequency(dash-dot) variation.

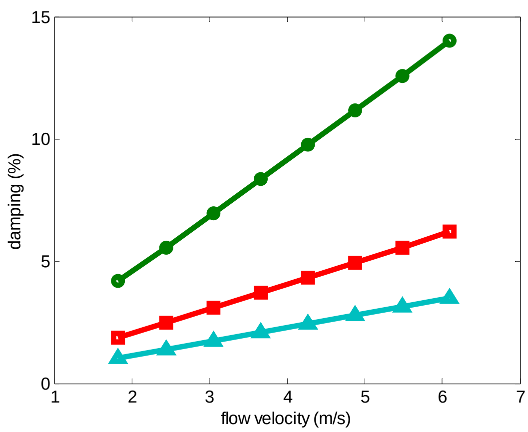

Fig. 2. Variation of the damping of the other modes (circle : 2nd mode, square : 3rd mode, triangle : 4th mode).

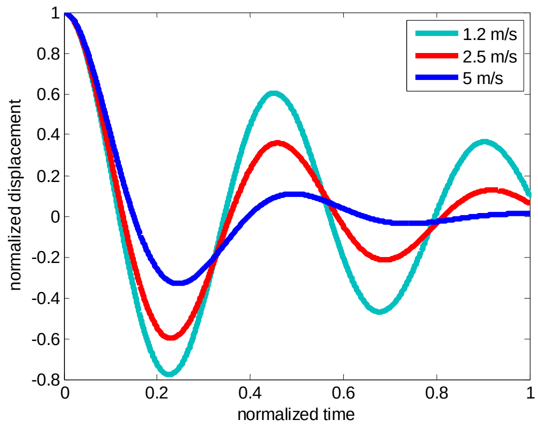

Fig. 3. Vibration behavior of the structure with various axial flow speed.

3. Conclusions

Submerged slender structural behavior is quite dependent on the flow condition. Especially the PWR fuel in the reactor should consider axial flow. This paper suggested a mathematical model of the slender structure. The physical meaning of the model is described, and the simulation results with the model are also provided. Actual damping due to the fluid is nonlinear, therefore further works are required to explain the detail behavior with the nonlinearity. The model validation test is on-going in KEPCO Nuclear Fuel, but it is believed that performance of the model is well correlated to the published work[4]. Finally, it is emphasized that the added damping considering the flow speed compensates for the loss of the structural integrity due to the long period operation.

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