Temperature and Flow Rate Dependent Green's Function Method for Fatigue Monitoring of Nuclear Power Plants

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1. Introduction

The concept of a stress-based fatigue monitoring system is based on the Green's function method (GFM) which provides a very fast calculation of the thermal stresses for given thermal transient time histories [1-3]. In this paper, for an actual on-line fatigue monitoring of nuclear power plants, the Green's function method combined with a numerical weight function is proposed to consider the effects of the flow rate of a coolant and the temperature-dependent material properties such as the thermal conductivity, specific heat coefficient, thermal expansion coefficient, density, and elastic modulus. The proposed method is verified for a pressurizer spray nozzle by detailed finite element analyses with an assumed critical thermal transient load case.

2. Methods and Results

This section includes the proposed method of the fatigue monitoring of the nuclear power plants by the stress-based Green's functions and the main results of the verification with an assumed thermal transient operation.

2.1 Temperature-Dependent Green's Function

In this paper, the modified GFM is proposed with the weight function introduced in Duhamel's integration scheme as follows;

$$\sigma_T(p,t) = \int_0^t G(p,t-\tau)W(\phi)\frac{\partial}{\partial\tau}\phi(\tau)d\tau \qquad (1)$$

In above equation, $W(\phi)$ indicates the weight functions dependent on bulk temperature ϕ. For the actual numerical integrations, Eq. (1) can be rewritten with the discritized form as follows;

$$\sigma_T(p,t) = G_s(p)[\phi(t)-\phi_{ref}]W_S(\phi) + \sum_{t-t_d}^{t}\overline{G}(p,t-\tau)\Delta\phi(\tau)W_T(\phi) \qquad (2)$$

where $W_S(\phi)$ and $W_T(\phi)$ is the weight functions for steady state condition and transient condition respectively. In Eq. (2), the first term in left side is for steady state calculations and the second term is for transient calculations. Thus, two types of weight functions are required to be determined for the modified GFM [4].

2.2 Flow Rate-Dependent Green's Function

The temperature dependent weight functions for a condition of the coolant flow have to be prepared by the same procedures of the section 2.1 and the thermal stresses are calculated adaptively with consideration of the flow conditions as follows;

$$\sigma_T(p,t) = Adaptive\begin{bmatrix} \int_0^t G_N(p,t-\tau)W_N(\phi)\frac{\partial}{\partial\tau}\phi(\tau)d\tau, \\ \int_0^t G_F(p,t-\tau)W_F(\phi)\frac{\partial}{\partial\tau}\phi(\tau)d\tau \end{bmatrix} \qquad (3)$$

Above equation, G_N and G_F are the Green's functions for no-flow and flow condition respectively and the W_N and W_F are the corresponding weight functions.

2.3 FE Model of Spay Nozzle

Fig. 1 presents the axisymmetric finite element model by using the ANSYS program. The spray nozzle consists of two materials of austenitic stainless steel (316 SS) for the thermal sleever and the inside clad surface, and carbon steel (SA 508) for the base metal of the nozzle. The cladding part and the coolant filled in the annulus gap between the thermal sleever and nozzle is modeled for only thermal analysis and eliminated for a stress analysis.

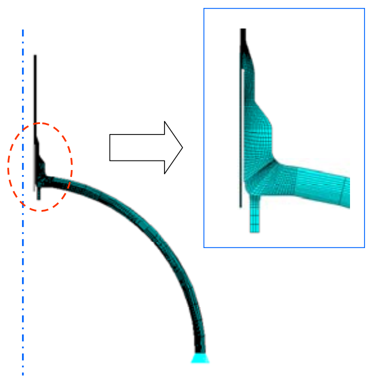

Fig. 1. Axisymmetric FE model of Spray Nozzle

2.4 Green's functions

The calculated Green's functions at the monitoring point are presented in Fig. 2 for the radial, axial, hoop, and shear stress components. Among the Green's functions, the hoop stress component is dominant and the all stresses reach to the steady state after 2000 seconds of cut-off time. Therefore, the cut-off time for a numerical integration of Eq. (2) is determined to be 2000 seconds in this paper.

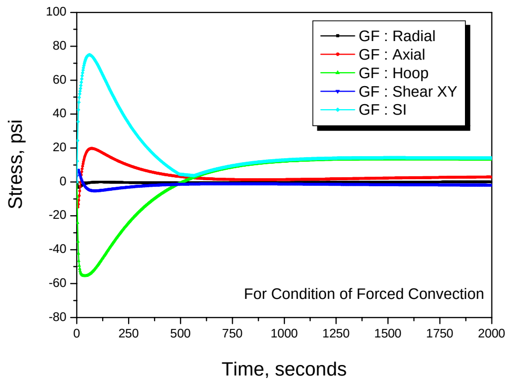

Fig. 2. Green's Functions for a Spray Condition

2.5 Verification Results

By using the determined weight functions, the thermal stress calculations are performed by using the GFM with VMP conditions and the detailed finite element analyses are done to verify the proposed method in this paper.

Fig. 3 presents the comparison results of the hoop stress time histories calculated by the GFM and the FEM to verify the temperature dependent Green's function method, i.e. considering variable material properties (VMP) with temperatures.

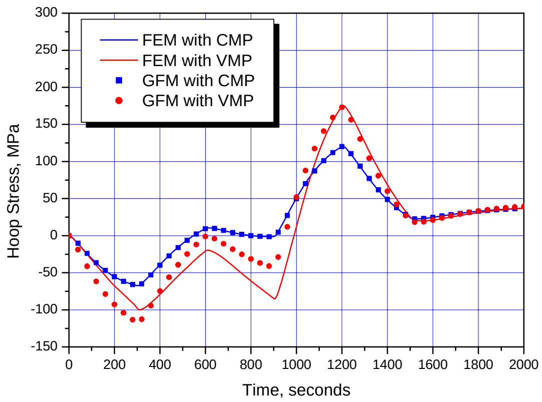

Fig. 3 Verification Results of Temperature-Dependent GFM

As shown in the results, we can see that the GFM gives exactly the same results as FEM in the case of CMP (constant material properties regardless of temperature) but results in severe discrepancies compared with the VMP conditions. However, the maximum stresses calculated by the GFM with VMP condition are in good agreement with those of the detailed finite element analyses with VMP. This means that the determined weight function for a steady state is reasonable and the proposed numerical method of Eq. (2) is useful to consider the temperature dependency of material properties.

Fig. 4 shows the verification results of the proposed method with a consideration of both the temperature and flow rate dependent effects. As shown in the results we can see that the proposed method results in a good prediction of the peak thermal stress values in an actual nuclear power plant operating condition.

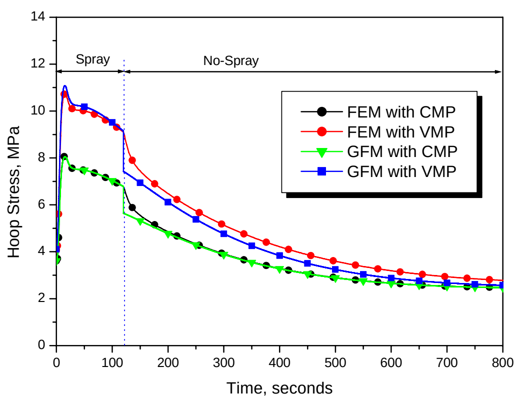

Fig. 4 Verification of the Temperature and Flow Rate-Dependent Green's Function Method

3. Conclusions

From the results, it is found that the temperature-dependent material properties and the flow rate can significantly affect the maximum thermal stress calculations when using the Green's function method. Therefore, to monitor a fatigue damage by using the Green's function method for real operating conditions in a nuclear power plant, it is required to consider the temperature-dependent material properties and the flow rate effects.

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