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Prediction of PT Diametral Creep for Wolsung NPPs

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1. Introduction

The PT diametral creep is caused mainly by fast neutron irradiation, temperature and applied stress. The currently used PT diametral creep prediction model considers the complex interactions between the effects of temperature and fast neutron flux on the deformation of PT zirconium alloys. The model assumes that long-term steady-state deformation consists of separable, additive components from thermal creep, irradiation creep and irradiation growth [1]. This is a mechanistic model based on measured data. However, this model has high prediction uncertainty. The aim of this study was to develop a bundle position-wise linear model (BPLM) to predict PT diametral creep employing previously measured PT diameters and HTS operating conditions. The aim of this study was to develop a bundle position-wise linear model (BPLM) to predict PT diametral creep employing previously measured PT diameters and HTS operating conditions. The BPLM was optimized by the maximum likelihood estimation method. The developed BPLM to predict PT diametral creep was verified using the operating data of the Wolsung nuclear power plant.

2. Bundle Position-wise Linear Model

2.1 Linear Model

A linear model is a flexible generalization of ordinary least squares regression. In this paper, the linear model was optimized using a genetic algorithm to easily impose some constraints to the regression coefficients and accomplish global minimization. The linear model is generally described as follows:

$$y_{ij} = a_{ijo} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \gamma_{ij} \quad (1)$$

where p is the number of input variables. Variables x_1 to x_p are the input signals that represent the fast neutron fluence, temperature, EFPD, etc. y is the output signal, which indicates the PT diametral creep or PT diameter. The parameter γ_{ij} indicates the measurement errors that is assumed to be independent and identically normally distributed with a mean zero and standard deviation σ_γ. Therefore, a true normalized differential diameter is as follows:

$$y_{ij}^t = a_{ijo} + a_{i1}x_{ij1} + a_{i2}x_{ij2} \quad (2)$$

Since the measured channels are assumed to be a random sample from the population of all 380 reactor channels in several effective full power day (EFPD) conditions, the true normalized differential diameter y_{ij}^t can be modeled as a random value as follows:

$$y_{ij}^t = a_{i0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \delta_j \quad (3)$$

where a_{i0} is a parameter that is common to the same bundle position of all channels and δ_j is independent and identically normally distributed with a mean zero and standard deviation σ_δ. δ_j reflects the channel-to-channel variability and is called the aleatory error. That is, a bundle position-wise linear model (BPLM) was devised because it is expected that the bundle position affects the diametral creep. The BPLM is described as follows:

$$y_{ij} = a_{i0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \varepsilon_{ij} \quad (4)$$

The appropriate selection of training data is very important because it can affect the optimization of the BPLM model. A BPLM model can be well trained using informative data. In this paper, the Subtractive Clustering (SC) scheme [2] is used to obtain more informative training data.

2.2 Maximum Likelihood Estimation

Since a CANDU PT channel has 12 bundles ($M = 12$), 12 BPLM models will be developed from n ($n = M \times J$) training input-output data sets. J indicates the total number of channels. The BPLM is described as follows, as shown in Eq. (4)

$$y_{ij} = a_{i0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \varepsilon_{ij} = \mathbf{x}_{ij}\mathbf{a}_i + \varepsilon_{ij} \quad (5)$$

The following likelihood function is used to solve the model coefficient $\boldsymbol{\alpha}$ with the covariance $\mathbf{V}$ [3]:

$$L\left(y;\boldsymbol{\alpha},\mathbf{V},\sigma_\delta^2,\sigma_\gamma^2\right) = (2\pi)^{-n/2}\left|\mathbf{V}\right|^{-1/2} e^{\left(-\frac{1}{2}(\mathbf{y}-\mathbf{X}\boldsymbol{\alpha})^T\mathbf{V}^{-1}(\mathbf{y}-\mathbf{X}\boldsymbol{\alpha})\right)} \quad (6)$$

The log-likelihood function is defined as

$$\begin{aligned} l &= \ln L\left(y;\boldsymbol{\alpha},\sigma_\delta^2,\sigma_\gamma^2\right) \\ &= -\frac{n}{2}\ln(2\pi) - \frac{1}{2}\ln\left|\mathbf{V}\right| - \frac{1}{2}(\mathbf{y}-\mathbf{X}\boldsymbol{\alpha})^T\mathbf{V}^{-1}(\mathbf{y}-\mathbf{X}\boldsymbol{\alpha}) \end{aligned} \quad (7)$$

To express the variances of the measurement error and the aleatory error in PT diameters rather than the normalized value, a scale factor s_ω should be multiplied in σ_δ^2 and σ_γ^2. The variances estimated by the maximum likelihood method are necessarily biased. The unbiased estimates of the variances can be solved taking the expectation of the biased variances. The prediction interval (PI) with 95% confidence is defined as

$$PI_{ij} = \hat{y}_{ij} + t_{0.05/2}^{n-3M}\left(\sqrt{Var(\lambda_{ij})}\right) \quad (8)$$

3. Application to the diametral creep prediction

The data used consisted of a total of 588 input-output data pairs $(x_1, \cdots, x_3, y)$ taken from the Wolsung nuclear power plant units 2, 3 and 4 (WS2, WS3 and WS4). This data was acquired at 1501, 1944 and 3256 effective full power days (EFPDs) from unit 2, and 1324, 2183 EFPDs from unit 3, and 937, 2154 EFPDs from unit 4. In this paper, all units are considered to have the same type (material and composition) of pressure tubes. The data of 39 channels that consist of 80 percent of a total of 49 measured channels from units 2, 3 and 4 were used to develop the BPLM models.

Table I provides the root mean squares (RMS) error and maximum error according to the bundle position. The error is the largest in the bundle position 10. Table II summarizes the uncertainties of the BPLM model. Here σ_ε, σ_δ, and σ_γ represent the standard deviation, the aleatory error and the measurement error, respectively.

Fig.1 shows prediction performance for BPLM model and Fig. 2 shows the prediction intervals for test data at a specific channel.

Table I: Errors according to the bundle position

Bundle position	Training data		Test data	
	RMS error (mm)	Max. error (mm)	RMS error (mm)	Max. error (mm)
1	0.0719	0.1827	0.0654	0.1316
2	0.0840	0.2630	0.0716	0.1511
3	0.0950	0.2988	0.0791	0.1460
4	0.0975	0.2908	0.0799	0.1396
5	0.0984	0.2732	0.0801	0.1510
6	0.1039	0.2756	0.0821	0.1627
7	0.1046	0.2793	0.0837	0.1666
8	0.1085	0.2588	0.0933	0.1826
9	0.1098	0.2426	0.0987	0.1926
10	0.1155	0.2867	0.1009	0.2002
11	0.1058	0.2822	0.0877	0.1915
12	0.0867	0.1925	0.0680	0.1455

Table II: Uncertainties of the BPLM model

Data type	σ_ε (mm)	σ_δ (mm)	σ_γ (mm)	Epistemic error (mm)	RMS error (mm)
Train data	0.1032	0.0936	0.0394	0.0211	0.0992
Test data	0.0995	0.0936	0.0394	0.0210	0.0833

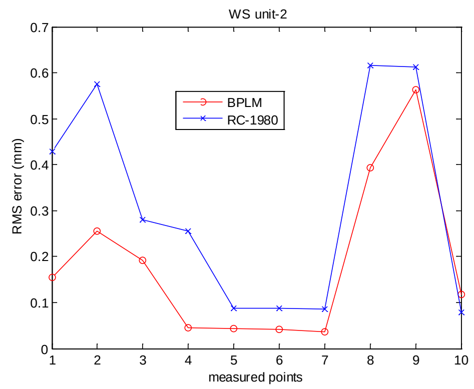

Fig. 1 Prediction performance for BPLM model

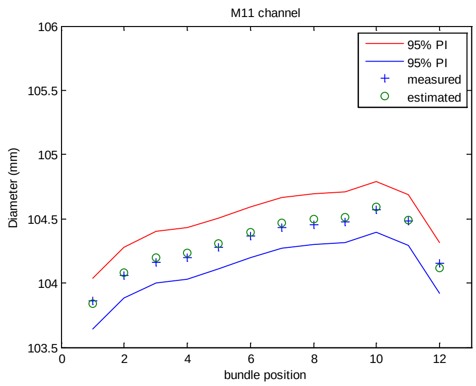

Fig. 2 Prediction interval for test data (Unit 2, M11 channel, 1501 EFPD)

4. Conclusion

A BPLM was developed to predict PT diametral creep using the previously measured PT diameters and the HTS operating conditions in CANDU reactors. The linear model was devised based on bundle position because it is expected that each bundle position in a PT channel has inherent characteristics. The proposed BPLM for predicting PT diametral creep was verified using the operating data of the Wolsung nuclear power plants. Although all the simulation results are not represented in this abstract, it is known from the uncertainty analysis that almost every data exists in the prediction intervals and the performance of the BPLM is superior to the existing RC-1980.

REFERENCES

[1] N. Christodoulou et al., “Modeling In-Reactor Deformation of Zr-2.5Nb Pressure Tubes in CANDU Power Reactors,” *Zirconium in the Nuclear Industry: Eleventh International Symposium*, ASTM STP 1295, E. R. Bradley and G. P. Sabol, Eds., American Society for Testing and Materials, pp. 518-537, 1996.
[2] S. L. Chiu, “Fuzzy Model Identification Based on Cluster Estimation,” J. Intell. Fuzzy Systems, 2, 267, 1994.
D. Quach, Development of a Wolsung Units 2, 3, and 4 Best-
[3] Estimate with Uncertainty Pressure Tube Diametral Creep Model, KE001/RP/001 R00, June 18, 2010.