Dynamic Compensation of Thermo-couple Responses for Core Temperature Measurement of Fast Reactors

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1. Introduction

Monitoring of the core temperature of fast reactors provides a crucial reactor protection function. In current SFR (Sodium-cooled Fast Reactors) design has multiple thermocouples housed inside a thermo-well of fuel subassemblies. The response time of the thermocouple assembly is an important input for safety system of fast reactor and hence frequent calibration/time constant estimation is essential. The determination of the time constant of thermocouples in thermo-well is a key factor of safety system design of SFRs. The thinner thermo-well structure can give the faster response time but it could give more fragile to creep, vibration and thermal fatigue. This paper demonstrates how effectively compensate the response time of thermocouples with modern digital filter techniques. The H_∞ filter[1] is applied for that purpose of dynamic compensation of delayed signal. The simulation results show robust and consistent dynamic compensation capability of the H_∞ filter for applying SFR core protection system.

2. Methods and Results

In this section we describe the dynamic model of the typical thermocouple in thermo-well. The details of the model can be found in [2] and we adhere the derivation therein.

2.1 Thermocouple Model

Figure 1 is a typical thermocouple in thermo-well and its lumped-parameter second order dynamics of the thermocouple and thermo-well in Laplace domain can be given by

$$\frac{V_{o(S)}}{V_{i(S)}}=\frac{1}{\{(1+\tau_1 S)(1+\tau_2 S)\}} \qquad (1)$$

where, V_o is output voltage, , V_i is input voltage and the various values of the time constants τ_1 and τ_2 are summarized in Table1. Now let us define $y=\mathrm{v_o(t)}$, $u(t)=v_i(t)$ and $y=x_1$, $\dot{x}_1=x_2$, then the resulting time-domain model can be represented by eq. (2).

$$\dot{x}=\begin{bmatrix} 0 & 1 \\ -\frac{1}{\tau_1\tau_2} & -\frac{\tau_1+\tau_2}{\tau_1\tau_2} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} 0 \\ \frac{1}{\tau_1\tau_2} \end{bmatrix}u(t) \qquad (2)$$

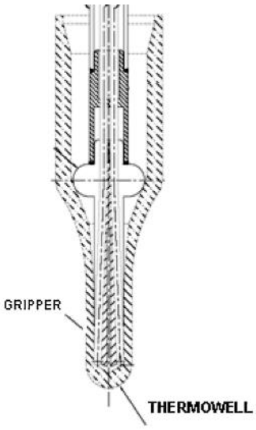

Figure 1. A typical thermocouple in thermo-well

Table 1. Time constants of thermocouples [2]

	τ_1	τ_2
cases	0.9433	24.3006
	0.9424	12.1816
	0.9415	8.1425
	0.9398	5.3970
	0.9396	4.6706
	0.9382	4.1866
	0.9378	3.9446
	0.9372	3.7028
	0.9358	3.2195
	0.9348	2.9780
	0.9319	2.4961

2.2 H_∞ Filtering Theory

The H_∞ filter[1] is applied with an Linear Matrix Inequalities (LMIs) sense as follows. A linear time-invariant discrete-time system given by

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Dw_k \\ z_k &= Lx_k \end{aligned} \qquad (3)$$

where x in R^n is the state vector, y in R^r is the measurement output vector, w in R^q is a disturbance vector containing measurement noise and z in R^p is the signal to be estimated. The matrices *A*,*B*,*C*,*D* and *L* are real and of appropriate dimensions. We are interested in designing a filter of the form

$$\begin{aligned} \hat{x}_{k+1} &= A\hat{x}_k + K(y_k - C\hat{x}_k) \\ \hat{z}_k &= L\hat{x}_k \end{aligned} \qquad (2)$$

where $K \in R^{nxr}$ is the filter constant gain to be determined.

The state estimation error is defined by $e_k \equiv x_k - \hat{x}_k$, then the error dynamics is given by

$$e_{k+1} = (A - KC)e_k + (B - KD)w_k \qquad (3)$$

$$\tilde{z}_k = z_k - \hat{z}_k = Le_k$$

The important feature of the *H∞* filtering problem is to get the estimate $\hat{z}_k$ of the signal z_k by minimizing the norm of the worst-case estimation error $\| e \|_2$ for all bounded energy disturbance w, that is,

$$\min \| H_{we} \|_\infty = \min \sup_{w \in l_2[0,\infty)} \frac{\| e \|_2}{\| w \|_2} . \qquad (4)$$

where H_{we} is the transfer function from the disturbance *w* to the estimation error *e*. The gamma-suboptimal H∞ filtering problem is defined to find (if it exists) a filter such that $\| H_{we} \|_\infty < \gamma$, where the positive scalar gamma is a prescribed noise attenuation level. The detailed description of the LMI based *H∞* filtering theory can be found in [1].

The unknown input signal is inversely estimated by

$$\hat{u}_k = (B^T B)^{-1} (\hat{x}_{k+1} - A\hat{x}_k) . \qquad (5)$$

2.3 Results of dynamic compensation

Fig. 2 shows the simulation results for in-core thermo-couples step responses with eleven cases of time constants given in Table 1. For all cases of the simulation, the response times are longer than 20 seconds. The response time for unit step signal is defines as the time to reach 0.65. Fig. 3 shows the dynamic compensation result with *H∞* filter for those eleven cases which show very consistently 1~2 seconds for all cases. The compensated signals are perfectly matches with the reference step signal.

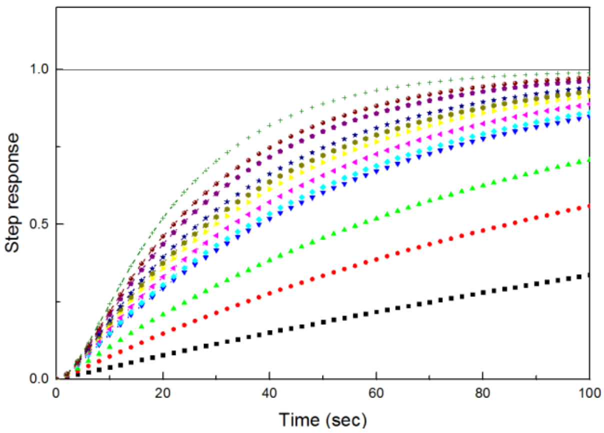

Figure 2. Unit step responses for temperature as a function of τ_1 and τ_2

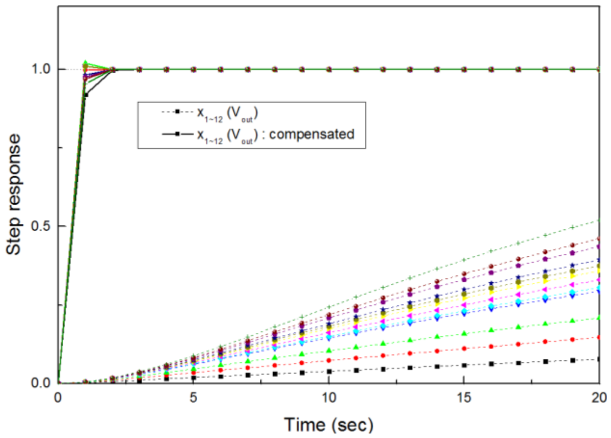

Figure 3. *H∞* filtered unit step responses for temperature as a function of τ_1 and τ_2

3. Conclusions

In-core thermo-couple measurements is necessary to assure the safety requirements of fast reactors. The periodic temperature measurements have to be performed also to ensure that the reactor protection limits are maintained. To respect the requirements, we need the reference model signal to find the aging or irradiation induced degradation of the thermo-couples. A novel dynamic compensation method is proposed based on the *H∞* filter. It is also demonstrated the applicability the *H∞* filter by simulation. The test result shows the proposed method can be a viable applied to the reactor protection system of fast reactors.

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