OPTIMAL PROCESSOR FOR MALFUNCTION DETECTION IN OPERATING NUCLEAR REACTOR

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ABSTRACT

An optimal processor for diagnosing operational transients in a nuclear reactor is described. Basic design of the processor involves real-time processing of noise signal obtained from a particular (in core) sensor and the optimality is based on minimum alarm failure in contrast to minimum false alarm criterion from the safe and reliable plant operation view-point.

1. INTRODUCTION

As plant ages, the probability of major reactor component failing increases, causing the operational status of the reactor be less safe and reliable. Such a status is termed as anomalous operation and identification of anomalous operation conditions in their incipient stage is imperative since even small degradations in plant performance can result in large material and man-power costs together with the costs due to interrupted operation. One of the sensitive techniques for malfunction sensing and diagnosis in a nuclear reactor is the noise analysis applied to the signals obtained from various sensors as the reactor is rather rich of noise signals to be exploited. Among these mention may be made to coolant flow turbulent, fission process, heat transfer, boiling etc. Although noise analysis is a powerful method for malfunction detection due to its sensitivity to the plant status, it requires complex techniques of signal processing, analysis and interpretation. Implementation of the malfunction detection processor in suboptimal form and its application for optimal operation is given before [1,2] where signal is assumed to be gaussian. In both cases operation of the processors are based on fixed number of samples causing relative delay in reporting anomaly in contrast to variable number of samples implemented in this work for plant surveillance.

2. BASIC DESIGN OF THE PROCESSOR

Basic design of the processor is carried out by means of autoregressive (AR) modeling of the noise signal in hand which yields a stationary band limited white noise sample sequence called residual noise. The residual noise is assumed to be stationary in normal operation so that any anomaly would impose on this stationary signal some change as an indication of malfunction.

As a basic processor, we define 'detection level' (ℓ_0) in such a way that, any residual noise amplitude exceeding this level in either polarity for a symmetrical probability density function (pdf) is counted to be anomaly. To determine the detection level use is made of simple hypothesis testing where null hypothesis H_0 is given by

H_0 : 'anomaly is not present' against the hypothesis H_1
H_1 : 'anomaly is present.

Let the corresponding pdfs be $f(x|0)$ and $f(x|P)$ and the associated Type I and Type II error probabilities in the statistical terminology be α and β respectively. Assuming any anomaly would indicate a special operational status termed as 'alarm' then the false alarm (FA) and alarm failure (AF) probabilities , p_{FA} and p_{AF} respectively, are given by Binomial distribution of the form

$$p_{FA} = 1 - \sum_{i=0}^{k} \binom{n}{i} \alpha^i (1-\alpha)^{n-i} \tag{1}$$

$$p_{AF} = \sum_{i=0}^{k} \binom{n}{i} \bar{\beta}^i (1-\bar{\beta})^{n-i} \tag{2}$$

where n is the number of samples being processed; k, the number of samples exceeding the detection level ℓ_0 and

$$\bar{\beta} = 1 - \beta \tag{3}$$

as the pdf of the residual noise. α and $\bar{\beta}$ are schematically shown in Fig. 1.

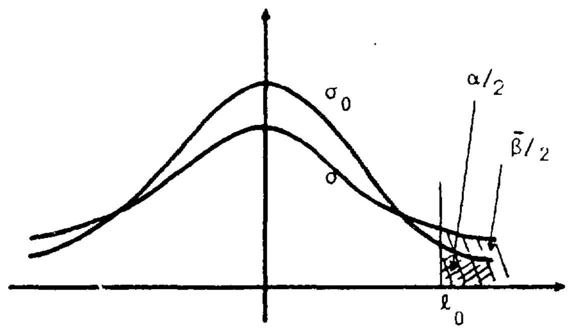

Fig. 1. Schematic representation of pdf of the residual noise and the parameters α and $\bar{\beta}$

The decision for reporting an anomaly is made in two levels. In level one, the alarm status is identified as described above. In level two, the relative value k, i.e. k/n is defined as 'level of significance' (ℓ_s) upon which decision is made for reporting malfunction. The level of significance can be determined by means of the criterion based on the confidence in decision upon which malfunction is declared. This can be accomplished considering the probability of failure in continuous surveillance as FA action.

For a white noise process, the number of samples k forms a Bernoulli process and this can be expressed by

$$P_n(n) = \binom{n-1}{k-1} \alpha^k (1-\alpha)^{n-k} \quad n=k,\ k+1,\ k_2+2,\dots \tag{4}$$

if we consider a sampling time interval Δt small compared to the time necessary for malfunction detection, Bernoulli process can be approximated by Poisson process of the form

$$f_t(t) = \frac{\lambda^k t^{k-1} e^{-\lambda t}}{(k-1)!} \quad t \geq 0 \tag{5}$$

where f(t) is the pdf of having k samples in time t and λ is the number of samples exceeding the detection level α per unit time. λ is given by

$$\lambda = \frac{\alpha}{\Delta t} \tag{6}$$

In Eq. 5, k takes positive integer values as describing the number of samples. On the other hand, if k is replaced by a continuous variable κ taking any positive value, $f_t(t)$ becomes gamma pdf

$$f_t(t) = \frac{\lambda(\lambda t)^{\kappa-1} e^{-\lambda t}}{\Gamma(\kappa)} \tag{7}$$

which has a cumulative pdf F(t) given by

$$F(t) = \frac{1}{\Gamma(\kappa)} \int_0^{\lambda t} u^{\kappa-1} e^{-u} du \tag{8}$$

and denoted by $\Upsilon(\lambda t, \kappa)$ as incomplete gamma function.

From the safe and reliable reactor operation view-point AF and FA probabilities, respectively, have to be minimized. The minimization of AF for a prescribed FA probability, can be accomplished by setting the detection level ℓ_o approximately in conjunction with the intensity of the anomaly as this is schematically shown in Fig. 2, and can readily be described for a Gaussian signal case [2].

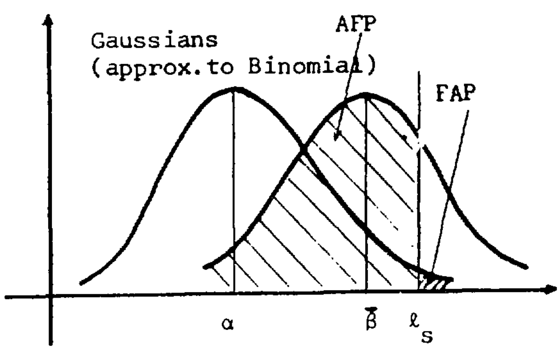

Fig. 2. Schematic representation of AF, FA probabilities in connection with the level of significance (ℓ_s).

On the other hand, for FA, one can make assessment by noting that FA can be viewed as a failure in a surveillance task and this eventually suggests the question of reliability in an alarm action; namely a malfunction detection processor is said to exercise a failure if its action is false, e.g. a FA. From this view-point, the alarm reliability function (R(t)) i.e., reliability of non-FA is expressed by

$$R(t) = 1 - \frac{1}{\Gamma(k)} \int_{0}^{\lambda t} u^{k-1} e^{-u} du = 1-\gamma(\lambda t, k) \tag{10}$$

Above, R(t) = 1-F(t) is the probability that the processor did not fail prior to time t. In the terminology of reliability $f_t(t)$ seen in Eqs. 5 and 7 is called failure probability density.

The ratio

$$h(t) = \frac{f_t(t)}{R(t)} \tag{11}$$

is defined to be conditional failure rate or "hazard rate" with units of inverse time. Hence it follows that the reliability function is given by

$$R(t) = \exp\left[-\int_{0}^{t} h(t')dt'\right] \tag{12}$$

From Eqs. 7 and 11, hazard rate h(n) is computed from

$$h(n) = \frac{\lambda(\alpha n)^{k-1} e^{-\alpha n}}{\Gamma(k)\ R(n)} \tag{13}$$

where $\alpha n = \lambda t$. In case the conditional failure rate is known, alarm reliability is computed by the help of Eq. 12.

3. ALARM RELIABILITY ASSESSMENT IN ANOMALY DETECTION

For a prescribed FA probability, the optimal detection level (ℓ_o/σ_o) which minimizes AF probability and the corresponding FA and AF probabilities for a Gaussian signal case, is given by [3]

$$\left(\frac{\ell_o}{\sigma_o}\right)^2 = \frac{2(\sigma/\sigma_o)^2 \ln(\sigma/\sigma_o)}{(\sigma/\sigma_o)^2-1} \tag{14}$$

$$FAP = \tfrac{1}{2} - \mathrm{erf}\left(\frac{\ell_s-\alpha}{\{\alpha(1-\alpha)/n\}^{\frac{1}{2}}}\right) \tag{15}$$

$$AFP|_{min} = \tfrac{1}{2}\left[1+\mathrm{erf}\left(\frac{\ell_s-\bar{\beta}}{\{\bar{\beta}(1-\bar{\beta})/n\}^{\frac{1}{2}}}\right)\right] \tag{16}$$

respectively, where erf(•) is the error function defined by

$$\mathrm{erf} = \left(\frac{2}{\sqrt{\pi}}\right)\int_0^x e^{\frac{1}{2}t^2}dt.$$

The computed AF probability assessments for given FA probabilities are presented in Table I for a gaussian optimal anomaly detection processor where number of samples processed is fixed as n=512.

In contrast to fixed number of samples for processing, data acquisition time for getting k samples exceeding the level, ℓ_o can be considered as a measure of abnormality expressed in terms of alarm reliability. To this end, for a given σ/σ_o ratio, optimal detection level ℓ_s is computed from eq. 14 and α, R(n) and h(n) are determined afterwards for prescribed k and n samples.

The results of the studies for implementation of an optimal gaussian processor based on alarm reliability criterion are presented in Tables II-IV where, in the first place, failure rate h(n) increases rather rapidly as the elapsed time raises, indicating diminishing probability for the presence of anomaly or in other words increasing probability for FA.

Table I. False alarm (FA) and alarm failure (AF) probability assessments for the optimal gaussian anomaly detection processor for $n = 512$.

σ/σ_0	ℓ_0/σ_0	FAP	ℓ_{s_0}	$AFP\|_{min}$
1.049	1.024	10^{-2}	0.353	0.880
		10^{-3}	0.369	0.973
		10^{-4}	0.382	0.994
		10^{-5}	0.393	0.999
		10^{-6}	0.403	1.000
1.225	1.103	10^{-2}	0.316	0.007
		10^{-3}	0.331	0.041
		10^{-4}	0.343	0.122
		10^{-5}	0.354	0.253
		10^{-6}	0.363	0.415
1.414	1.177	10^{-2}	0.283	1.270×10^{-8}
		10^{-3}	0.297	3.541×10^{-7}
		10^{-4}	0.309	4.882×10^{-6}
		10^{-5}	0.319	3.853×10^{-5}
		10^{-6}	0.329	2.096×10^{-4}

Table II. Alarm reliability (R) and failure rate (h) assessment of the anomaly detection processor based on reliability criterion $k = 15$ $\sigma/\sigma_0 = 1.0490$ $\Delta t = 0.1$ s.

n	$R(n)$	$h(n)$
15	0.9999	0.0007
16	0.9998	0.0012
17	0.9997	0.0020
18	0.9994	0.0034
19	0.9990	0.0053
20	0.9983	0.0080
21	0.9974	0.0116
22	0.9960	0.0164
23	0.9940	0.0226
24	0.9914	0.0303
25	0.9880	0.0396
26	0.9835	0.0507
27	0.9779	0.0637
28	0.9710	0.0787
29	0.9626	0.0955
30	0.9526	0.1143
31	0.9408	0.1349
32	0.9272	0.1572
33	0.9116	0.1812
34	0.8941	0.2067
35	0.8747	0.2335

Table III. Alarm reliability (R) and failure rate (h) assessment of the anomaly detection processor based on reliability criterion k = 15 σ/σ_0 = 1.2250 Δt = 0.1 s.

n	R(n)	h(n)
15	1.0000	0.0002
16	1.0000	0.0003
17	0.9999	0.0006
18	0.9998	0.0010
19	0.9997	0.0016
20	0.9995	0.0025
21	0.9992	0.0038
22	0.9987	0.0056
23	0.9981	0.0079
24	0.9971	0.0110
25	0.9958	0.0149
26	0.9941	0.0197
27	0.9919	0.0255
28	0.9890	0.0325
29	0.9854	0.0407
30	0.9810	0.0502
31	0.9755	0.0610
32	0.9690	0.0731
33	0.9613	0.0865
34	0.9524	0.1012
35	0.9420	0.1172

Table IV. Alarm reliability (R) and failure rate (h) assessment of the anomaly detection processor based on reliability criterion k = 15 σ/σ_0 = 1.4140 Δt = 0.1 s.

n	R(n)	h(n)
15	1.0000	0.0000
16	1.0000	0.0001
17	1.0000	0.0002
18	1.0000	0.0003
19	0.9999	0.0005
20	0.9999	0.0007
21	0.9998	0.0012
22	0.9996	0.0017
23	0.9994	0.0026
24	0.9991	0.0037
25	0.9987	0.0051
26	0.9981	0.0070
27	0.9973	0.0093
28	0.9962	0.0122
29	0.9948	0.0158
30	0.9930	0.0200
31	0.9908	0.0250
32	0.9880	0.0308
33	0.9847	0.0375
34	0.9806	0.0450
35	0.9758	0.0534

4. CONCLUDING REMARKS

Basic features of a gaussian processor devised for nuclear reactor surveillance are identified. For safe and reliable operation viewpoint alarm reliability and the conditional failure rate assessment are performed by means of associated reliability function.
The concept of reliability is rather conspicious in malfunction detection due to rapid response of the method which is based on the alarm reliability criterion. The detection level is an essential parameter of the processor and it can be levelled optimally begin particular type of anomaly kept eye on it, the optimality being defined as the minimized alarm failure in surveillance process. In general, in a nuclear reactor operation, since the nature of anomaly and the degree of its effect on the signal being observed is not known in advance, the establishment of the optimal processing conditions cannot be precisely set and therefore some deviations from the optimality in actual operation is unavoidable.

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