Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Fatigue Analysis on the Internals of Qinshan 600Mwe Nuclear Reactor in Flow-Induced Vibration Test Using the Extreme Value Distribution Method

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ABSTRACT A method analyzing the fatigue life of reactor's internals with extreme value distribution technique is presented in this paper. On the basis of giving the means to calculate the extreme loads, the testing load of Qinshan 600MW Reactor's internals was analyzed. It comes to the conclusion that the effect of the flow-induced vibration on the fatigue life of the reactor's internals during the design service life can be ignored and the valuable data for determination of the minimum record duration of reactor internals' flow-induced vibration test were given.

INTRODUCTION

Like some other engineering structural parts, nuclear reactor's internals usually bear random fatigue loads in service, which derived mainly from the flow-induced vibration. Accordingly, in designing internals of nuclear reactors, the effects of flow-induced vibration on their fatigue life must be considered.

Some references [1] have shown that the extreme load is the main cause contributing to the failure of engineering structural components. Thereafter, whether the extreme loads could be determined exactly or not will directly influence the credibility in evaluating the fatigue life of the structural parts in reactor.

In general, there are two methods to determine the extreme value loads, a. deduction from the cumulative frequency curve; and b. the extreme value distribution technique. The former has been used in engineering fields for many years, but the latter has been widely used long years before in such applications as estimating severe gust loads, ocean wave loads, earthquake loads and extreme pressure in meteorological phenomena and so on, and recently, it has been utilized to determine the failure loads of automotive structural parts etc[2].

In this paper, the extreme value distribution technique was utilized to analyze the random strain load history induced by flow and to deduce the fatigue life of Qinshan 600MW Reactor's Internals.

PROCESSING RANDOM STRAIN LOADS

The load history analyzed in this paper was the micro-strain load record gathered from the barrel. The measuring system was data sampling system of CDS Corporation of England together with American concurrent computer. The sampling frequency and data length were 2.5kHz and 18s respectively. The strain gage's position was shown in figure 1. The typical strain record sample is shown in figure 2. This random process is ergodic, that is, each sample has the same statistical property and therefore represents the whole population.

Possibility Distribution of Extreme Value Loads

Reactor's coolant will flow and excite the internals to vibrate randomly. The inspiring power are mainly turbulence and pumping-induced pressure pulse. Although the service load spectrum is generally quite complex, it can be divided into two types: a. the normal peak loads, and b. the extreme value loads. As we all known, both types of loads are random in their magnitude and frequency, but their statistical frequency distributions are quite different.

As we all known, it is somewhat difficult to determine the distribution of normal peak loads. But it is shown from reference [1] that most peak values of random variables in engineering conform to the normal distribution. The strain load records sampled from the barrel in flow-induced vibration test are analyzed statistically on computer and are proved to obey the normal distribution too, that is,

$$\xi \sim N(u, \quad \sigma^2) \tag{1}$$

Now that the random process is ergodic too, it is enough to consider only one sample with the time interval of $\triangle t$, in which every sample has an extreme value x , and the distribution function is $F_{\triangle t}(x)$. If dividing the testing time t into n number of same length interval $\triangle t$, and assuming every sample segment is independent or has little correlativity one another , their possibility distribution function F(x) can be expressed as:

$$F(x) = \left[F_{\Delta t}(x)\right]^n \tag{2}$$

Theoretical study has shown, when the testing time $t \to \infty$, the asymptotic possibility distribution function of the extreme value can be written as:

$$F(x) = \exp\{-\exp[-\alpha(x-\mu)]\} \tag{3}$$

Where, μ and α are distribution parameters , which can be gained through statistical processing on computer[3]. For more details of the underlying assumptions and the derivation of this distribution function, see Appendix.

Accordingly, assuming the extreme value distribution of this micro-strain history gathered from the barrel obeyed the double exponential distribution as Eq.3, after being statistically processed at similar time interval on computer , the results of distribution parameters μ and α are given in Table 1.

Table 1. The calculation results of distribution parameters μ and α

Δt (s)	0.02	0.04	0.06	0.10	0.08	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26
α (1/ v)	0.74	0.58	0.56	0.48	0.47	0.44	0.45	0.41	0.35	0.38	0.36	0.34	0.34
μ (v)	1.01	3.55	3.56	4.54	4.54	5.00	5.20	6.02	6.40	7.12	6.76	7.32	7.00

Determination of Minimum Measurement Time

As we all known, we could not measure the loads in all service life. Therefore, it is necessary to determine the minimum period of time so that it is statistically representative.

Let Δt_0 designate the lowest limit of the length of measurement time. If selecting a shorter one than Δt_0, the extreme value load derived from it cannot be applied validly for forecasting the load magnitudes and frequency occurring in the future service time, but any time interval longer than Δt_0 is perfectly valid and acceptable, which is of significance very much in engineering.

When the extreme value distribution function $F_0(x)$ associated with the minimum measurement time Δt_0 is expressed as:

$$F_0(x) = \exp\{-\exp[-\alpha_0(x-\mu_0)]\} \tag{4}$$

The extreme value distribution function $F_n(x)$ of any testing time Δt_n ($\Delta t_n = n\Delta t_0$, there n is integer) is

$$F_n(x) = \exp\{-\exp[-\alpha_n(x-\mu_n)]\} \tag{5}$$

Considering Eq.1,4 and 5, the famous Fisher-Tippet stability criteria can be obtained, that is,

$$\begin{cases} \alpha_n = \alpha_0 \\ \mu_n = \mu_0 + \ln n/\alpha_0 \end{cases} \tag{6}$$

Hence, through such relationship the minimum measurement time can be determined as follows:

Divide the measurement load history into equal Δt_1 segments and determine the maximum load value for each Δt_1 interval. Using the calculation method (3), estimate the distribution parameters α_1 and μ_1. Repeat this process for the next longer time interval Δt_2 and estimate similarly α_2 and μ_2.

Make plot of Δt_i's vs μ's and α's (Figure 3,4) using results shown in table 1.

This minimum measurement time Δt_0 is the one (in figure 4) beyond which the value of α remains constant, that is, there exists a horizontal asymptote on the figure 4.

Making use of the characteristics in figure 4, we can determine the minimum measurement time Δt_0. That is, Δt_0 =0.263s. Accordingly, α_0 and μ_0 are 0.335 (1/ν) and 7.003 (ν) respectively (where, ν represents micro-strain).

Estimate The Extreme Value Load Of Long Term

After the extreme value distribution function F(x) and the minimum measurement time Δt_0 are obtained, using the Eq.7 we can figure out the extreme load x_t associated with any longer service time t($t>\Delta t_0$):

$$x_t = \mu_0 + \ln(t/\Delta t_0)/\alpha_0 \tag{7}$$

In view of the aforementioned strain records, the extreme strain value can be gained with such method. Shanghai Institute of Nuclear Engineering had taken 30 years as the devised service life for the reactor's internals of Qinshan 300MW NPP[5]. Therefore, in this paper, the extreme strain value $\mathbf{x_{30}}$ is calculated at first:

$$x_{30} = 7.003 + \ln(30 \times 365 \times 24 \times 3600/0.26)/0.335 = 72.7(\nu)$$

Transferring x_{30} into the stress, it is 14.5 MPa.

Likewise, the extreme strain value x_{40} relative to 40 years service life can be calculated too, the transferred stress value is 14.7 MPa, which is almost the same as the calculation result in reference [6].

Owing of the fatigue stress much less than the fatigue devised limit 160MPa(4) of this material, the conclusion seem to be obtained that the flow-induced vibration has little effect on the barrel's fatigue strength.

Shanghai Institute of Nuclear Engineering has carried out the internals' fatigue analysis of Qinshan 300MW NPP reactor. Its conclusion is very similar to that of this paper.

QUALITY OF THE EXTREME VALUE

From Eq.7, we can find the quality of the extreme value as follows: the extreme value load increased with deduction time t, but when $t \to \infty$, the extreme value load can't tend towards infinite value. The reference [2] had ever analyzed the automotive road loads and presented that as the analytic sample length increases, the extreme value load would not increase infinitely, but tended to a constant.

In fact, making differentiation from Eq.7, we can see that:

$$d(x_t) = \frac{\Delta t_0}{\alpha_0 t} dt \tag{8}$$

So, as the deduction time increases, the increment of extreme value load gradually decreases. That is : $t \to \infty$, $d(x) \to 0$, $x_t \to constant$.

In this paper, the random strain history sampled from the flow-induced vibration test of Qinshan 600 MW reactor's barrel was analyzed, and the extreme loads associated with diverse service life are given (Table 2 and Figure 4).

Table 2. The extreme loads associated with diverse service life

service life (year)	10	20	30	40	50	60	70	80	90	100	110	120
extreme load (MPa)	13.9	14.3	14.5	14.7	14.9	15.0	15.1	15.1	15.2	15.3	15.3	15.4

It is apparent that there exists an asymptote on figure 4, therefore once more the conclusion is proved that the random fatigue load from flow-induced vibration had little effect on the fatigue life of Qinshan 600MW reactor's barrel.

CONCLUSION

a) The flow-induced vibration has little effects on the reactor internals' fatigue life of Qinshan 600MW nuclear power reactor's internals during the devised service life 40 years. This conclusion is the same as the result of the *Shanghai Institute of Nuclear Engineering*;

b) It is possible to provide valuable reference data for assuming the measurement time of reactor internals' flow-induced vibration test;

c) It is effective to analyze fatigue life of nuclear reactor's internals making use of the extreme value distribution method.

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APPENDIX

Let us consider a stress record history with the recording time t as a random process. We can divide it into n sub-sample with equal interval Δt, that is, $t=n \cdot \Delta t$, in which every sub-sample has a local maximum μ_i $(i=1,2,...,n)$, and let the distribution function of the local maximum be designated by $F_i(x)$, $f_i(x)$ being its probability density function. If this process is ergodic(i.e. each sample has the same statistical properties and therefore represents the whole population.), it is enough to analyze only one sample function.

Firstly, we can arrange n local maxima μ_i $(i=1,2,...,n)$ in the order of magnitude, that is,

$$\mu_1 \leq \mu_2 \leq \cdots \leq \mu_n \tag{A-1}$$

Assuming that these local maxima are independent one another, the distribution function $F(x)$ of the extreme value μ_n of whole population t can be expressed as:

$$F(x)= F_1(x) \cdot F_2(x) \cdot ... \cdot F_n(x) \tag{A-2}$$

In general, $F_i(x)$ obeys the *normal* or *exponential* function[1], so the Eq.2 can be written in the form:

$$F(x)= [F_i(x)]^n \tag{A-3}$$

Using the Taylor Series expand the distribution function of local maxima $F_i(x)$ in the neighborhood of the μ_n value, we can get:

$$F_i(x) = F_i(\mu_n) + \frac{(x-\mu_n)}{1!} F_i'(\mu_n) + \frac{(x-\mu_n)^2}{2!} F_i''(\mu_n) + \cdots + \frac{(x-\mu_n)^\nu}{\nu!} F_i^{(\nu)}(\mu_n) + \cdots \tag{A-4}$$

As μ_n is the extreme value among n local maxima μ_i, that is, μ_n is biggest in magnitude among them, the $F_i(\mu_n)$ can be expressed approximately as:

$$F_i(\mu_n) = 1 - \frac{1}{n} \tag{A-5}$$

Substituting the probability density function *f(x)* for the derivative of *F(x)* and Eq.5 into the Eq.4, we can obtain:

$$F_i(x) = 1 - \frac{1}{n}\{1 - \sum_{\nu=1}^{\infty} \frac{(x-\mu_n)^{\nu}}{\nu!} n f_i^{(\nu-1)}(x-\mu_n)\} \tag{A-6}$$

From this, with respect to the power series of e^{-x}, the following expression can be obtained:

$$F_i(x) = 1 - \frac{1}{n}\exp[-\alpha_n(x-\mu_n)] \tag{A-7}$$

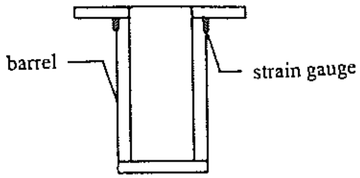
Where, $\alpha_n = n f_i(\mu_n)$

Taking into consideration Eq.3, we can derive the distribution of extreme value stress of whole population (that is $t \to \infty$) from the distribution of local maximum $F_i(x)$:

$$F(x) = \lim_{n\to\infty}[F_i(x)]^n = \lim_{n\to\infty}\{1 - \frac{1}{n}\exp[-a_n(x-\mu_n)]\}^n \tag{A-8}$$

Using the famous limit value of exponential function, and omitting the index n , the following asymptotic distribution function can be obtained for the extreme value stress:

$$F(x) = \exp\{-\exp[-a(x-\mu)]\} \tag{A-9}$$



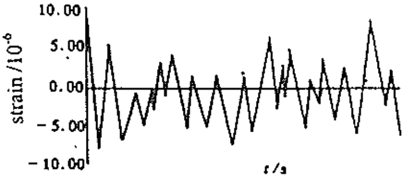
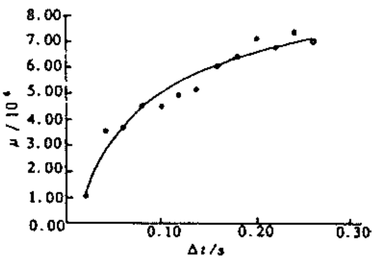


Figure 1. The position for measuring strain.

Figure 2. The typical strain analysis sample



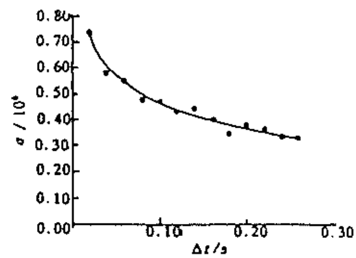


Figure 3. The relationship between distribution parameter μ and testing time Δt

Figure 4. The relationship between distribution parameter α and testing time Δt

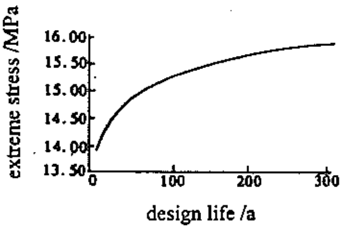


Figure 5. The relationship between diverse design life and extreme load value