Journal of the Korean Nuclear Society
Volume 30, Number 1, pp.8~16, February 1998

Development of Automatic Reactor Internal Vibration Monitoring System Using Fuzzy Peak Detection and Vibration Mode Decision Method

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(Received July 2, 1997)

Abstract

In this work a method to detect the vibrational peak and to decide the vibrational mode of detected peak for core internal vibration monitoring system which is particularly concerned on the core support barrel (CSB) and fuel assemblies is developed. Flow induced vibration and aging process in the reactor internals cause unsoundness of the internal structure. In order to monitor the vibrational status of core internal, signals from the ex-core neutron detectors are transformed into frequency domain. By analyzing transformed frequency domain signal, an analyst can acquire the information on the vibrational characteristics of the structures, i.e., vibration frequencies of each component, vibrational level, modes of vibration, and the causes of the abnormal vibration, if any. This study is focused on the development of the automated monitoring system. Several methods are surveyed to define the peaks in power spectrum and fuzzy theory is used to automatic detection of the vibrational peaks. Fuzzy algorithm is adopted to define the modes of vibration using the peak values from fuzzy peak recognition, phase spectrum, and coherence spectrum.

1. Introduction

1.1. Reactor Internal Structure and The Vibration Monitoring

Generally, the internal structure of a pressurized water reactor (PWR) is very complex. It consists of the CSB, the upper guide structure, the core shroud assembly, and the lower support structure[1]. The CSB is a large cylindrical structure. The lower core support structure, including the CSB, is supported by its flange which is joined to the reactor vessel flange, and its lower end is restrained from transverse motion by a radial support system attached to the vessel wall. The CSB is joined to the reactor vessel by the hold down spring (expansion ring), and the snubber supports it to prevent heavy distortion and movement. If there are thermal shields to prevent temperature increase of the reactor vessel, they are joined to the CSB by joints. The lower core plate is positioned at the bottom level of the core below the baffle plates and provides support for the fuel assemblies[2][3][4].

The coolant fluid which is injected through the reactor vessel inlet nozzle flows into the space between the reactor vessel and the CSB. This fluid causes the vibration of the core internal structure including the CSB and the thermal shield. It moves like a pendulum when it receives the vibrating force, because only the upper flange of the CSB is joined to the reactor vessel and the lower parts are free. This vibration is the representative mode of internal vibration and is called as pendulum mode or beam mode vibration. The CSB also shows the shell mode vibration because of its cylindrical geometry. The vibration of the internal structure appears as a mixture form of various mode vibrations. The separation of these vibrations does important role in monitoring and fault detecting of components.

It is very hard to measure the vibration directly in the reactor vessel. Therefore, the vibration of the internal structure (CSB, thermal shields and fuel assemblies) has to be measured indirectly. Generally, the available signals for the analysis of the CSB vibration are the noise signals from the ex-core and in-core neutron detectors, the signals from the accelerometers placed on the head of reactor vessel, and the signal disturbances of other process parameters. The reactor neutron noise analysis technique is developed to detect the change of the vibration.

1.2. Background and Objectives of This Work

The degradation of axial preload of CSB and the looseness of clamping element can cause significant core damages. In order to prevent this damage in advance, the monitoring system is needed. The 'Nuclear Power Experience' from 1963 to 1989 shows 58 failures of the PWR internal structure. These failures include 22 failures (38%) of the CSB and the thermal shield, 11 failures (19%) of the thimble tube, 6 failures (10%) of the irradiated surveillance specimen, 6 failures (10%) of loose parts, and 13 failures (23%) of others. The main causes of the CSB and the

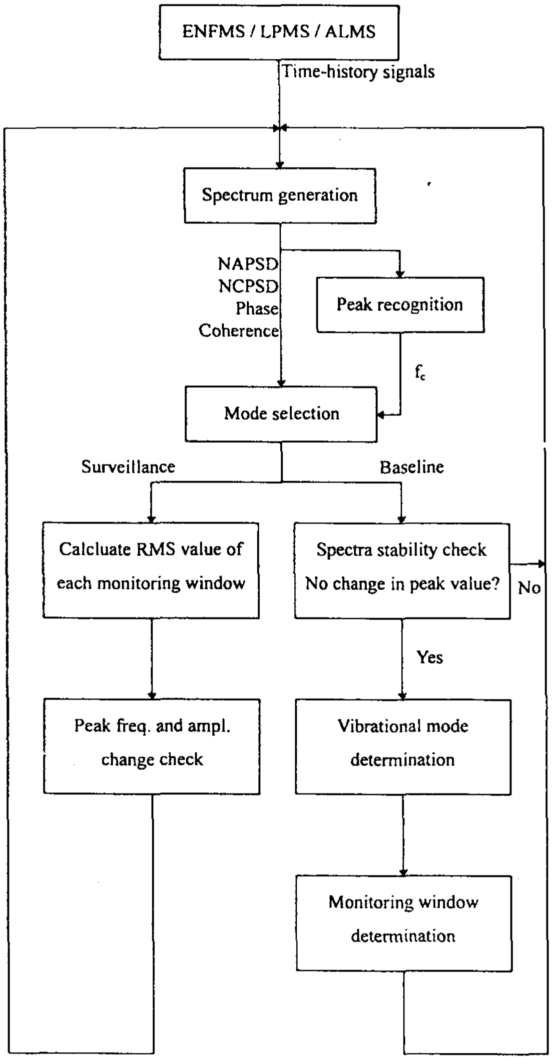

Fig. 1. The General Procedure for Vibration Monitoring of Mechanical Structrues

thermal shield failures are vibration (27.3%) and fatigue (22.7%). The looseness of the CSB flange joints is a severe problem which may directly affect on the integrity of the core supporting structure[3]. The change of the CSB beam mode vibration frequency implies the failure of joints between the CSB and the reactor vessel. The change of the fuel assembly swing vibration frequency implies the unsoundness of fuel assembly. It is also desirable to use some artificial intelligence techniques which recognize the change of frequency domain information in quick and accurate manners. Fuzzy theory is used for this purpose in this work.

This study is focused on the development of the automated monitoring system. Several methods are surveyed to define the peaks in power spectrum and fuzzy theory is used to automatic detection of the vibrational peaks. Fuzzy algorithm is also adopted to define the modes of vibration using the peak values from fuzzy peak recognition, phase spectrum, and coherence spectrum. By using fuzzy theory in vibrational peak recognition and its mode decision algorithm, the monitoring system can detect the abnormality of reactor internals in real time.

2. Automated Reactor Internal Vibration Monitoring

2.1. Conventional Procedure

The general procedure for vibration monitoring of mechanical structures is shown in Figure 1. Ex-core neutron flux monitoring system (ENFMS) provides time-history signals of ex-core detectors. Using fourier transform, one can generate various frequency domain spectra such as normalized autopower spectral density (NAPSD), normalized crosspower spectral density (NCPSD), phase spectrum, and coherence spectrum. Plant personnel can find peak frequencies (f_c) by investigating these spectra. He should also decide the mode of vibratory peaks. In baseline phase, he should check stability of spectra. When they are in stable condition, vibration mode and monitoring window should be determined. In surveillance phase, RMS value of each monitoring window is calculated and peak frequency and amplitude values should be checked.

Almost all of these procedures are performed separately and step by step by the plant personnel, which need special expertise[5]. In order to diagnose the vibrational state of the reactor internals, the plant personnel should be a expert in signal processing and in random data analysis. It follows that the results of each step depends on human analyzer' s decision.

The major steps which require the analyzer' s attention are the step of recognizing the vibrational peaks from the power spectrum, the step of defining the normal vibrational modes and monitoring windows, the step of detecting the changes in frequency and amplitude of the vibrational peaks in the power spectrum, and the step of providing the reason of the changes. If there is no human expert in plant, this procedure could induce mal-decision about reactor internal status because the steps listed above are very complex and need lots of experiences.

2.2. Data Acquisition and Peak Recognition

Vibration signal form the ex-core neutron flux detectors have been acquired from the ex-core neutron flux monitoring system (ENFMS) of Yonggwang nuclear power unit 3 (YGN 3) in Korea, and AC components of the signals have been extracted from DC signals. These signals have been transformed into frequency domain using FFT to generate auto-power spectral density (APSD), cross-power spectral density (CPSD), phase, and coherence functions.

Power spectral density :Sxy(f) = pF (1)

$$S_{xy}(f) = \int_{\infty}^{\infty} R(\tau) e^{-j2\pi f \tau} d\tau$$

Coherence function : (2)

$$\gamma_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f) S_{yy}(f)}$$

Phase angle : (3)

$$\theta_{xy}(f) = \tan^{-1} \frac{\mathrm{Im}[S_{xy}(f)]}{\mathrm{Re}[S_{xy}(f)]}$$

Vibrational peaks in power spectra are not deterministic and we can consider several methods to define the peaks from the vibration of mechanical structures. The general method is to fit the curves by polynomial equation.

$$g'(f) = a_n f^n + a_{n-1} f^{n-1} + \cdots + a_0 f^0 \quad (4)$$

where, a_k (k=0, ···, n) : constants.

When the real spectrum can be expressed as g(f), we can detect the peaks by comparing the difference between fitted curve (g′(f)) and the actual spectrum (g(f)). If the difference (g(f) - g′(f)) increases drastically in some area, we can determine that there are some peaks within that area[6]. This method is, however, not suitable for the case of using ex-core neutron signals because the power spectrum from the neutron signals is not deterministic which implies the possibility of containing non-deterministic peaks. That is, the peaks from FFT of ex-core neutron signals are not so clear (sharp) to use this method.

Another method is the pattern recognition which is generally used in neural network or neuro-fuzzy system. This method has many merits for use in the monitoring system. This method needs lots of pattern data for training to reduce the error of mal-decision. There exist, however, very few training data in abnormal condition of reactor internals.

Calculation of the RMS values of sliding range to check out the maximum RMS value can be used as a method to detect peaks. The sliding range is established considering possible existence of the peaks. This method requires well-tuned RMS band to avoid maximum RMS values with no peaks.

We could use fuzzy theory to detect peaks in the spectrums from FFT. In order to recognize the 'peak', this fuzzy method needs the definition of the 'peak'. We can use any shape which is similar to sharp peak as a definition of the peak. In this study, we chose shape of triangle. According to the features of each peak, this algorithm controls the shape of triangle which is used to find the peak. The rate of successful detection of peaks highly depends on the shape of the triangle. Therefore, sufficient pre-survey for specific peak features are required. This method, however, could recognize various kinds of peaks via fine tuning of the triangles.

All of these methods which are mentioned above - curve fitting method, pattern recognition using neural network, maximum RMS method, and fuzzy method - have been tried and the fuzzy algorithm is adopted in this study. In order to find the peak using triangles, we define the area of the reference triangle (S_{tri}) and the overlapping area(S_{over}) between the triangle and some peak.

$$S_{over} = \int_{f_0}^{f_1} \mathrm{MIN}[\mathrm{Reference}(f), \mathrm{spectrum}(f)] df \quad (5)$$

$$R = \frac{S_{over}}{S_{tri}} = \frac{\int_{f_0}^{f_1} \mathrm{MIN}[\mathrm{Reference}(f), \mathrm{spectrum}(f)] df}{\int_{f_0}^{f_1} \mathrm{Reference}(f) df} \quad (6)$$

R value can be expressed as the values between 0 and 1. This fuzzy number[7],[8] value can be used for the resemblance of the peak relative to the reference triangle as shown in Figure 2. A large value of R implies there is a peak. Triangle slides along frequency axis of the spectrum with the height of the deference between local maximum and local minimum, and checks the fuzziness of the peaks, consequently picks some frequency points as peaks. This method, as shown in Figure 3, is the most effective one of the three peak recognition algorithms mentioned above. Sample results from the fuzzy peak recognition algorithm are shown in Figure 4 with coherence between cross ex-core detectors in Figure 5 for ex-core neutron detector signal of YGN 3.

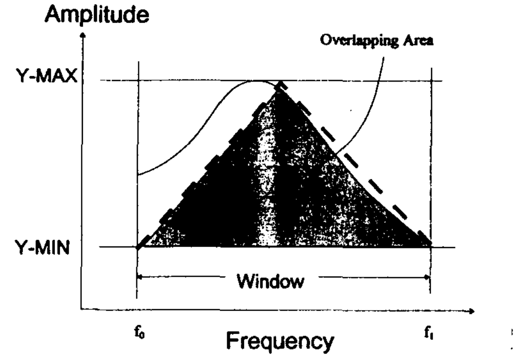

Fig. 2. The Illustration of the Fuzzy Peak Recognition by a Triangle

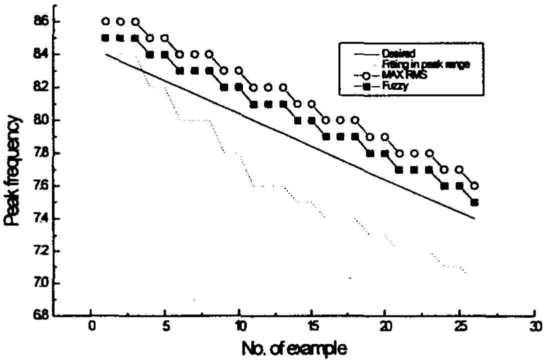

Fig. 3. Comparison of Errors from Three Different Peak Recognition Algorithm. They Were Applied to the data Between 3 Hz and 12Hz of Figure 4. In Order to Test the Perpormance of Each Method, Peak Frequency was Modified to Decrease Along Number of Example. Sliding Window Size of RMS Method and Fuzzy Method is Both 2.5Hz.

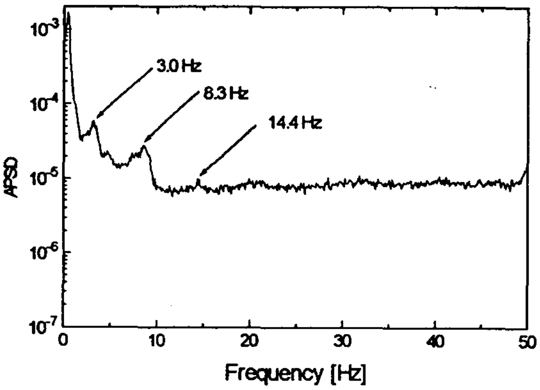

Fig. 4. Results of Fuzzy Peak Recognition

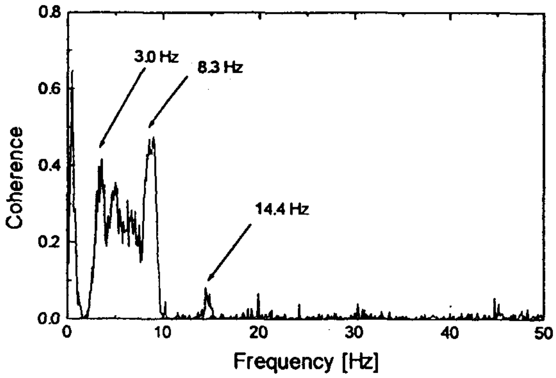

Fig. 5. Coherence Spectrum to Compare with the Results of Fuzzy Peak Recognition

Table 1. The Characteristics of CSB Shell Mode, CSB Beam Mode, and FA Bending Mode

Vibration Tye	Parameters			
	Detector Position	Center Frequency	Phase	Coherence
CSB shell mode	Adj.	16~26 Hz	160~200°	High
	Cross	16~26 Hz	340~20°	High
CSB beam mode	Adj.	6~15 Hz	340~20°	High
	Cross	6~15 Hz	160~200°	High
Fuel Assemblies 1st bending mode	Adj.	1.5~5.5 Hz	340~20°	Low
	Cross	1.5~5.5 Hz	340~20°	High

2.2. Defining Vibrational Modes Using Fuzzy Algorithm

Prior studies show the characteristics of power spectra from the ex-core neutron flux signals[9]~[11]. The modes of normal vibration have been defined based on these results. Input for this algorithm is the set of frequencies from peak recognition algorithm, phase data, and coherence data. This system has been made to define characteristics of CSB shell mode, CSB beam mode, FA bending mode, and unknown mode utilizing French experiences in pressurized water reactors[11] (PWRs). Monitoring windows have been determined according to the recommendation of ASME[12].

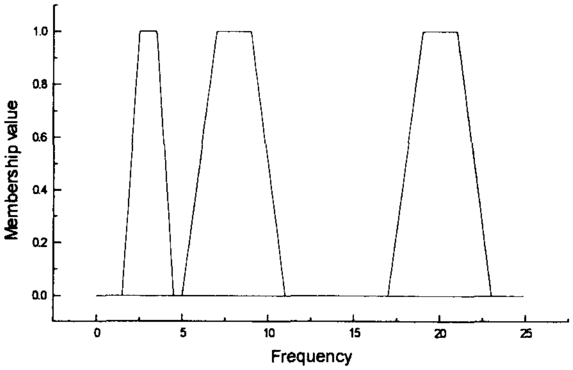

Fig. 6. Membership Function for Center Frequency

Table 1 shows the characteristics of CSB shell mode, CSB beam mode, and FA bending mode by four parameters (detector position, center frequency, phase, and coherence). Vibrational mode can be decided using this table. As shown in Table 2, we could define the content type for four parameters in order to decide the vibrational mode of detected peaks. One of them has three types and the others have two types.

We can fuzzify the parameter of peak center frequency using trapezoid membership functions which are shown in Figure 6. For the parameter of phase and coherence, we can also fuzzify using bell type membership functions which are shown in Figure 7 and Figure 8, respectively. The

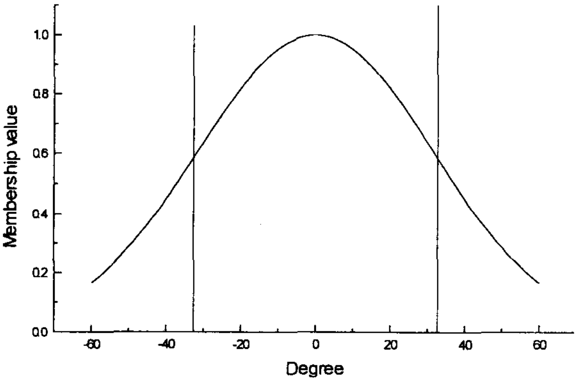

Fig. 7. Membership Function for Phase 0°

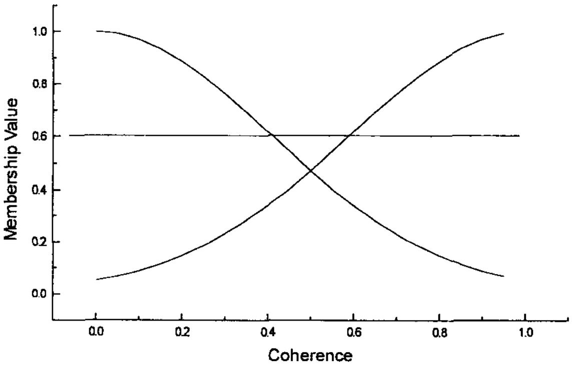

Fig. 8. Membership Function of Coherence

Table 2. The Content Type for Parameters(Detector Position, Center Frequency, Phase, and Coherence)

Parameter	Type 1	Type 2	Type 3
Detector Position	Adjacent	Cross	
Center Frequency	16 ~ 26 Hz	6 ~ 15 Hz	1.5 ~ 5.5 Hz
Phase	180°(160~200°)	0°(340~20°)	
Coherence	High	Low	

parameter of detector position does not have fuzzy value. It just has the binary value of 0 or 1.

Figure 9 shows a schematic diagram for the vibrational mode decision using fuzzy theory. After fuzzyfication phase, the system calculates minimum value of fuzzified parameters for each category. These categories are established using the data in Table 1.

Category 1 : $\Psi_1 = \mathrm{MIN}\,[\mu^{phase\text{-}180}, \mu^{coh\text{-}high}, \mu^{freq\text{-}20}]$ (7)

Category 2 : $\Psi_2 = \mathrm{MIN}\,[\mu^{phase\text{-}0}, \mu^{coh\text{-}high}, \mu^{freq\text{-}20}]$ (8)

Category 3 : $\Psi_3 = \mathrm{MIN}\,[\mu^{phase\text{-}0}, \mu^{coh\text{-}high}, \mu^{freq\text{-}8}]$ (9)

Category 4 : $\Psi_4 = \mathrm{MIN}\,[\mu^{phase\text{-}180}, \mu^{coh\text{-}high}, \mu^{freq\text{-}8}]$ (10)

Category 5 : $\Psi_5 = \mathrm{MIN}\,[\mu^{phase\text{-}0}, \mu^{coh\text{-}low}, \mu^{freq\text{-}3}]$ (11)

Category 6 : $\Psi_6 = \mathrm{MIN}\,[\mu^{phase\text{-}0}, \mu^{coh\text{-}high}, \mu^{freq\text{-}3}]$ (12)

From these minimum values for categories (Equation (7) to Equation (12)), the system calculates maximum value.

Adjacent detectors : $P_{adj} = \mathrm{MAX}[\Psi_1, \Psi_3, \Psi_5]$ (13)

Cross detectors : $P_{cross} = \mathrm{MAX}[\Psi_2, \Psi_4, \Psi_6]$ (14)

Then, the system checks that this value exceeds criterion. If this value exceeds the criterion (in this study, we assign the criterion as 0.6 by

Table 3. Results of the Automated Fuzzy Vibration Monitoring System

Center Frequency	Phase	Coherence	Mode of vibration
3.0 Hz	162°	0.41	Fuel Assembly 1st bending mode
8.3 Hz	178°	0.48	CSB beam mode
14.4 Hz	6°	0.1	Unknown

Table 4. The Typical Causes of Changes in Reactor Vibrational Spectrum

Parameter	Type of change	Structure	Reason
Center Frequency	Decrease	Fuel Assembly	Decrease in stiffness
		CSB	Reduction in holddown force
Amplitude	Increase	Fuel Assembly	Decrease in stiffness with radiation exposure
		CSB	Reduction in holddown force

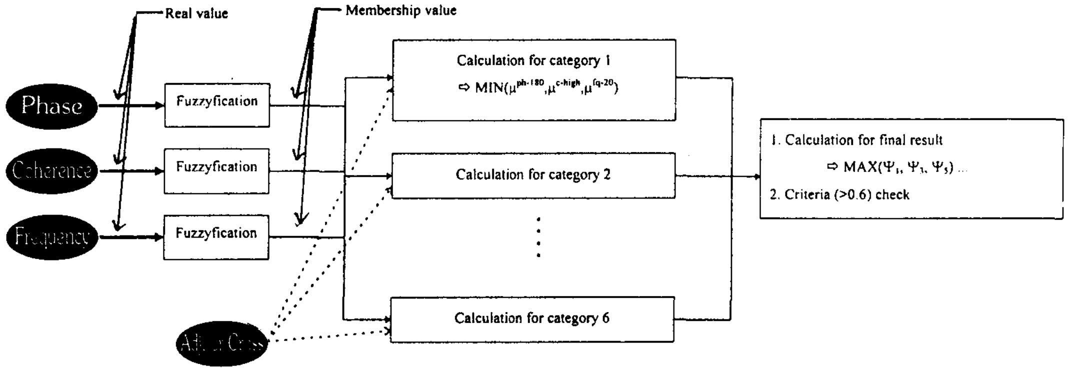

Fig. 9. The Schematic Diagram for the Vibrational Mode Decision Using Fuzzy Theory

investigating plant signals), the system decides that input peak belong to selected category (maximum value category).

2.3. Results

Time-history signals of Yonggwang nuclear unit 3 have been acquired and transformed into frequency domain. Fuzzy algorithm to recognize the vibrational peaks in power spectrum has picked three frequencies as follows :

3.0 Hz, 8.3 Hz and 14.4 Hz.

The phase data have been averaged over ten points with respect to the peak points to reduce signal processing error. These values (peak center frequencies, phase, and coherence) have been used as inputs to the fuzzy algorithm to define each mode of vibration. The results are shown in Table 3. The vibration of 14.4 Hz has not been known. Further investigation could provide the knowledge on this peak. The automated system can monitor the reactor internal continuously and detect the changes in frequency and amplitude, providing the typical causes of the changes. The typical causes of changes in reactor vibrational spectrum can be summarized as Table 4.

3. Concluding Remarks

The automation of the monitoring system for the vibration of reactor internals has been performed using fuzzy algorithm. This helps the plant personnel diagnose the vibrational state of the reactor internals even though he is a novice in signal processing and random data analysis. Peak recognition has been performed using fuzzy concept of the peaks and vibrational modes have been defined by the fuzzy algorithm for the power spectra from the ex-core neutron signals.

This system relieves the plant personnel from the burden of decision-making by incorporating the knowledge of the experts in reactor noise analysis. The vibrational characteristics of different reactors, however, are not yet investigated. Other study to complement this respect is strongly suggested.

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