

ACOUSTIC MONITORING FOR FLUIDIZED BED BOILERS

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Abstract: The newly developed monitor watches the fluidized condition of FBC (Fluidized Bed Combustor), referring to acoustic signals which are collected by heating tubes in the beds and passing to tube acceleration sensors outside the fluidized Beds. The monitor, without any observation hole or special probes, not only detects the bad-fluidized region, which requires proper operations for preventing from agglomeration, but also diagnoses conditions of the boiler equipment. The monitor adopts the joint time-frequency analysis technique to the acoustic signals as well as considers non-Gaussian properties, on decision making procedure, including skewness and excess of parameter distributions which are the resulting characteristics through the analyses on the time-frequency plain. The monitor has been applied to an 350MWe FBC for testing, and validated through one and a half year operation

Keywords: acoustic monitor, time-frequency analysis, non-Gaussian

1 INTRODUCTION

Figure 1 shows a construction of the monitor for FBC, which consists of a wind box for supplying air through throat, bed materials of pulverized lime stone with coal, and steam heating tubes submerged by the materials. Since the bad-fluidized region not only lowers heat transfer to tubes but also tend to be the gradually growing agglomeration which spoils the bed, the technique for early detection of such region has been strongly required to operate the plant properly. In this report, the newly developed monitor for FBC, which does not require any observation hole or special probes, will be introduced. This monitor shall be appreciated its applicability of only putting acceleration sensors on heating tubes outside the fluidized Beds.

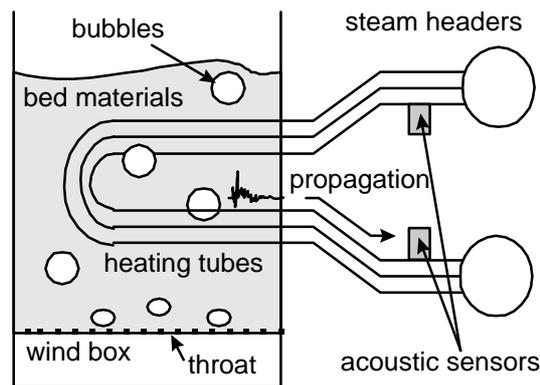


Fig.1 Acoustic monitor for FBC

Figure 2 is a flow diagram for signal processing from acoustic sensors outside the bed to monitor inside. Through the flow diagram, the monitor adopts the joint time-frequency analysis technique to the acoustic signals as well as, on decision making procedure, considers non-Gaussian properties including skewness and excess of parameter distributions which are the resulting characteristics through the analyses on the time-frequency plain. The features of these functions on the flow diagram will be mentioned in the following sections.

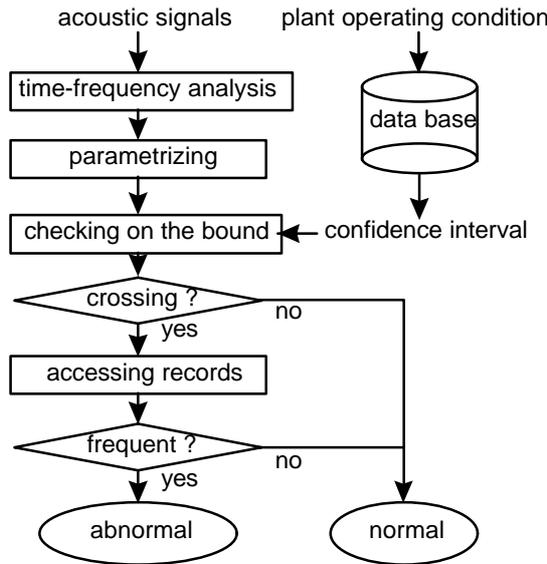


Fig.2 Decision flow of acoustic monitoring

2 TIME-FREQUENCY ANALYSIS

The acoustic signal $x(t)$ is passing the anti-aliasing filter and sampled and numerically transformed into the time-frequency plane $(b, f) = (b, w_0/2\pi a)$ in every one minute, applying Gabor wavelet $f(t; w_0, s)$ as follows:

$$X(b, f) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{a}} f\left(\frac{t-b}{a}; w_0, s\right) dt = \int_{-\infty}^{\infty} x(t) \sqrt{\frac{2\pi f}{w_0}} f\left(\frac{2\pi f(t-b)}{w_0}; w_0, s\right) dt \quad (1)$$

$$\text{where } f(t; w_0, s) = \frac{1}{\sqrt{2\pi s}} \exp\left\{-jw_0 t - \frac{1}{2}\left(\frac{t}{s}\right)^2\right\} \text{ with } \int_{-\infty}^{\infty} f(t) dt = 0 \quad \int_{-\infty}^{\infty} |f(t)|^2 dt = 1 \quad (2)$$

Figure 3 is an example of the heating tube acceleration signal projected on the time-frequency plane. The technique appear to be suitable for detecting transient or intermittent phenomena to which conventional Fourier Transform technique is hard to be applied.

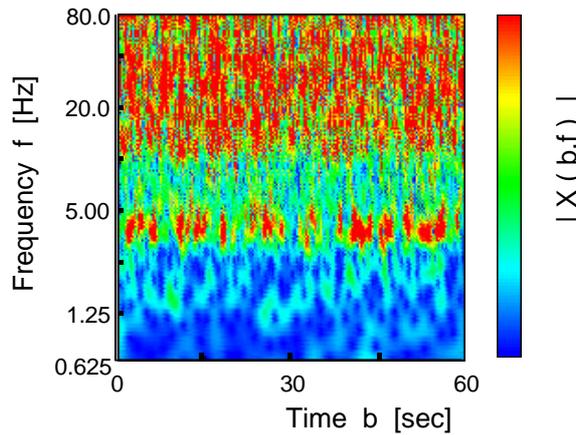


Fig.3 Example of time-frequency analysis

3 PARAMETRIZING

Then transformed $|X|^2 = XX^*$ is to be parametrized at time b as follows:

$$1) \text{ peak frequency: } f_{\text{peak}}(b) = \arg\left\{\max_f \left(|X(b, f)|^2\right)\right\} \text{ on } (f_1 \leq f < f_2) \quad (3)$$

$$2) \text{ normalized } k\text{-th moment: } r_k(b; \mathbf{l}, \mathbf{r}) = \int_{f_1}^{f_2} \left(\frac{f - \mathbf{l}}{\mathbf{r}}\right)^k |X(b, f)|^2 df \text{ for } (0 \leq k \leq 4) \quad (4)$$

- 3) frequency of over threshold in a time interval.
- 4) smoothed time trend

Figure 4 shows examples of above four parametrizing. Concerning 4) distribution case, the normalized k -th moment has sufficient information for describing the distribution with Edgeworth series in Eq.(7); however, the distribution for the parametrizing does not have properties for probability theory.

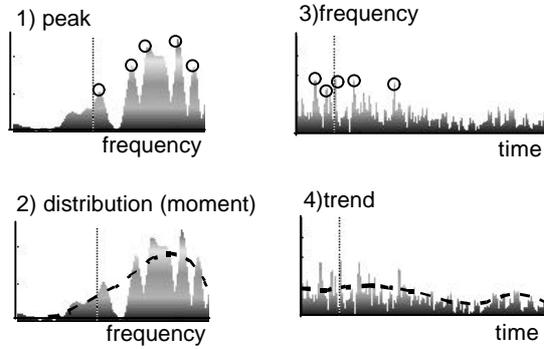


Fig.4 Example of parametrizing

4 DATA BASE

In normal status, each parameter in previous section, peak frequency etc., forms sequence $\{\Xi_{m,i}\}$ which represents values of a parameter at time $b_{m,i}$, namely $\Xi_{m,i} = \Xi(b_{m,i})$ ($b_{m,i} \in \mathbf{A}_i$) where \mathbf{A}_i denotes a set of time interval associated with the i -th plant operation, the same plant load etc. Figure 5 shows the concept of the sequence depending upon the operating conditions. Since $\Xi_{m,i}$ should be assumed to be random variables, in the data base, managing upper and lower bound of the confidential interval is to consider the probability density function (p.d.f) corresponding to operating condition i . The way of managing the boundary is all the same to each parameter and operating condition; thus, the sequel argument will be carried on without the subscript i .

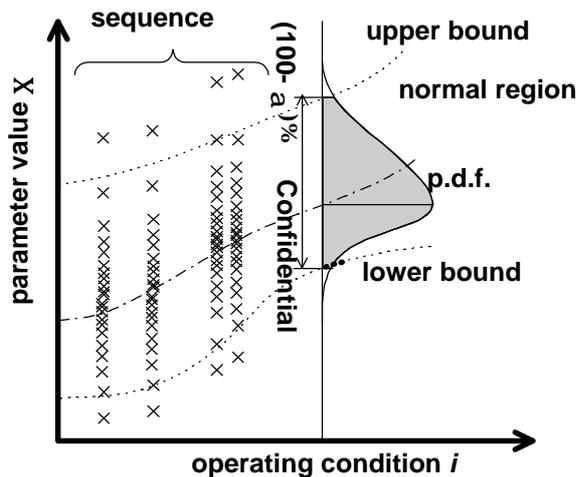


Fig.5 Confidential interval of each operating condition

Firstly, in order to evaluate probability distribution of each parameter in previous section, the following normalized j -th moment are calculated.

$$v_j(\mathbf{I}, \mathbf{r})^j = (1/n) \sum_{m=1}^n ((\Xi_m - \mathbf{I})/\mathbf{r})^j \quad (5)$$

Then the following semi-invariant (mean, variance, skewness and excess, in order) are memorized in the data base.

$$k_1 = m = v_1(0,1), k_2 = s^2 = v_2(m,1), k_3 = v_3(m,s), k_4 = [v_4(m,s) - 3] \quad (6)$$

Applying the following truncated Edgeworth series, $g(x)$ of the seeking p.d.f. takes shape in Fig.6.

$$g(x) = \frac{1}{\sqrt{2ps}} \exp\left\{-\frac{1}{2}\left(\frac{x-m}{s}\right)^2\right\} \left[1 + \frac{k_3}{3!} H_3\left(\frac{x-m}{s}\right) + \frac{k_4}{4!} H_4\left(\frac{x-m}{s}\right) + \frac{k_3^2}{6!} H_6\left(\frac{x-m}{s}\right)\right] \quad (7)$$

where the following j -th order Hermitian polynomial are used.

$$\begin{aligned} H_1(x) &\equiv 1, H_2(x) \equiv x^2 - 1, H_3(x) \equiv x^3 - 3x, H_4(x) \equiv x^4 - 6x^2 + 3, \\ H_5(x) &\equiv x^5 - 10x^3 + 15x, H_6(x) \equiv x^6 - 15x^4 + 45x^2 - 15 \end{aligned} \quad (8)$$

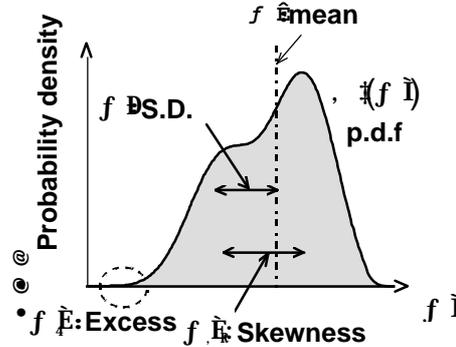


Fig.6 Probability density function (p.d.f) described with the Edgeworth series

In this connection, the order of Hermite polynomial has a useful property in differentiation as follows:

$$\left(\frac{d}{dx}\right)^n \Phi(x) = (-1)^n H_n(x) \frac{1}{\sqrt{2p}} \exp\left\{-\frac{1}{2}x^2\right\} \quad (9)$$

where $\Phi(x)$ denotes the following standard Gaussian distribution.

$$\Phi(x) = \frac{1}{\sqrt{2p}} \int_{-\infty}^x \exp\left\{-\frac{1}{2}x^2\right\} dx \quad (10)$$

For evaluating probability, the Edgeworth series (7) is integrated as follows:

$$G(x) = \int_{-\infty}^x g(z) dz = \Phi\left(\frac{x-m}{s}\right) - \frac{1}{\sqrt{2p}} \exp\left\{-\frac{1}{2}\left(\frac{x-m}{s}\right)^2\right\} \left[\frac{k_3}{3!} H_2\left(\frac{x-m}{s}\right) + \frac{k_4}{4!} H_3\left(\frac{x-m}{s}\right) + \frac{k_3^2}{6!} H_5\left(\frac{x-m}{s}\right)\right] \quad (11)$$

Consequently, the seeking upper/lower x_2/x_1 bound of $(1-a) \times 100$ [%] confidence interval with a % false alarm rate is obtainable through the following relations.

$$\Pr\{x_1 < \Xi \leq x_2\} = G(x_2) - G(x_1) = 1 - a \quad \text{with} \quad G(x_1) = \frac{a}{2}, \quad G(x_2) = 1 - \frac{a}{2} \quad (12)$$

where the following Newton method will be applied to convergence with given tolerance ϵ .

$$x_1^{k+1} = x_1^k - \frac{G(x_1^k) - \frac{a}{2}}{g(x_1^k)} \quad (\text{until } |x_1^{k+1} - x_1^k| < \epsilon) \quad (13)$$

5 VALIDATION AT PILOT PLANT

Figure 7 shows a pilot plant of FBC where some throats can be blocked for making the bad-fluidized region. In this testing, acceleration sensors are set on eight tubes, which are numbered from channel 1 to 8 as in Fig.7; by the way, many tubes without sensors are not illustrated in the figure.

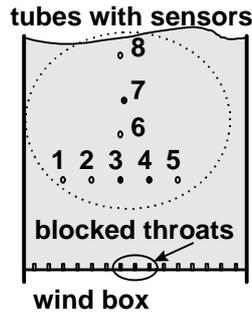


Fig.7 Air flow blocking test on a pilot plant

An example of the result is in Fig.8, which is comparing normal and abnormal with blocked throat operations. In this result, acceleration signal from each channel are evaluated of the 95% confidential interval of normalized second moment, namely variance, of 6.25-800Hz portion on the time-frequency plane. According to the example, there is remarkable difference between normal and abnormal cases in 100% air flow operation on channel 4 near blocked throat; while, no notable difference on channel 8 far from the simulated bad-fluidized region. The result validates that watching the normalized second moment parameter of time-frequency analysis can detect the bad-fluidized region near a heating tube with an acceleration sensor.

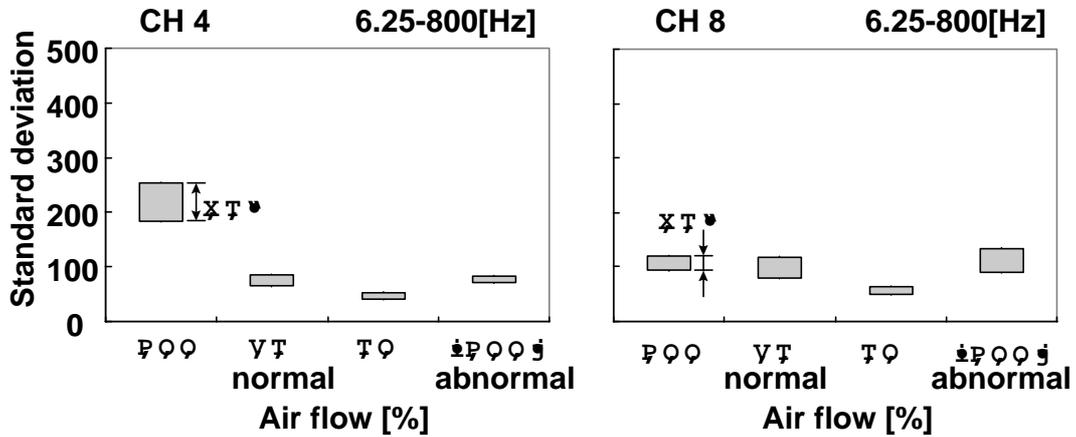


Fig.8 Confidential interval of signal second moment parameter

6 FIELD TESTING

After validation at a pilot plant, the monitoring system in this report had been applied to a 350MWe FBC at Takehara thermal power station in Hiroshima prefecture, Japan. In the field testing, the developed monitoring system consists ten acceleration sensors on heating tubes shown in Fig.9, signal processor, man-machine communicator and gateway for referring plant control signals to obtain operating condition, such as electrical load etc., as subscript i shown in Fig.5.

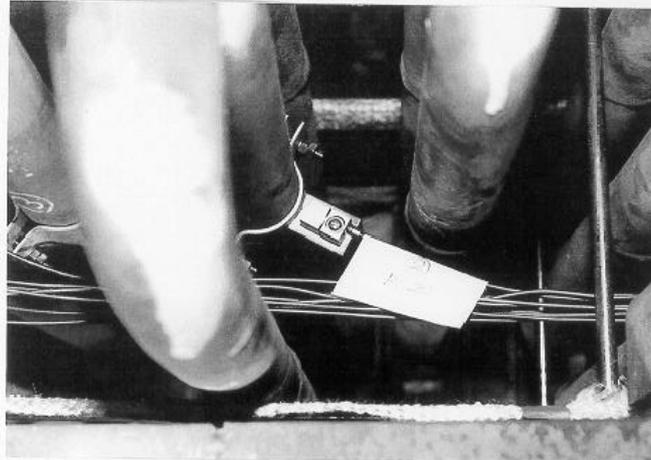


Fig.9 Acceleration sensors on heating tubes in 350MWe FBC

Figure 10 is an example of monitoring function at the power station. The system has the data base for upper/lower bound of 95% confidential interval of 0-th order moment, namely energy parameter, of the time-frequency plane which is depending upon the electrical load as a plant operating condition shown in Fig.10. Through a half year operation of the field testing from July 1999, the monitoring system has been correctly watching 0 to 4 th order normalized moment of the acceleration signals designated area on the time-frequency plane whether crossing the boundary of the confidential interval or not. So far there has been no case of frequently passing the boundary; on the other hand, no bad-fluidized region such as agglomeration has been found through detailed inspection of the plant. Thus we can confirm that the developed monitor has been properly worked in actual power station for one and a half year.

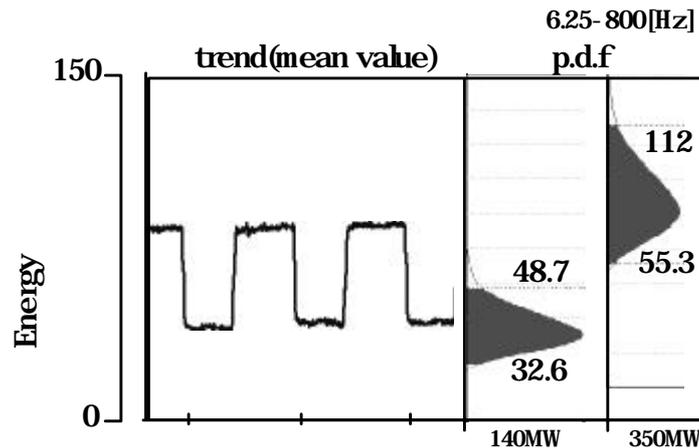


Fig.10 upper/lower bound of energy parameter

7 CONCLUSIONS

The newly developed monitor to watch the fluidized condition of FBC has the following features:

- 1) Referring to acoustic signals collected by heating tubes in the beds to detect the bad-fluidized region without any observation hole.
- 2) Adopting the joint time-frequency analysis technique to the acoustic signals.
- 3) On decision making procedure, considering non-Gaussian properties including skewness and excess of parameter distributions.
- 4) Applied to a 350MWe FBC for testing, and validated its functions through one and a half year operation.

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