A Real Time Multi-Scale Correlation Analysis Method and Its Application on The Data Mining in Thermodynamic Process

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***Abstract*—There is a complicated mapping between the state and measurement signal in the complex thermodynamic system, direct mechanism analysis is very difficult. Using wavelet analysis idea for reference, simple filter bank was designed to decompose the signal by frequency domain. The correlation feature of signals in different frequency scale can be discovered. Using such method to analyze furnace pressure signal of boiler in thermal power plant, the positive correlation between the low-frequency component of furnace pressure signal and the medium-frequency component of fuel was revealed; and the negative correlation between the high-frequency component variance of furnace pressure signal and the low-frequency component of fuel was discovered. Through further mechanism analysis the conclusion is that: the furnace pressure can reflect the change of the furnace temperature in medium-frequency; the intensification of the furnace pressure and furnace temperature fluctuation in boiler under low load condition is cased by the nonlinearity of object itself.**

Keywords- complex thermodynamic system; furnace pressure; frequency analysis; multi-scale filter; feature extraction

I. INTRODUCTION

The interaction between the state variable and the measurement signal of the thermal process was very complicated. So it is difficult to analyze the process by mechanism analysis method. Using the data analysis method the history data of the process were pretreated, and then change law and interaction of some signals were revealed, on the basis of which the further mechanism analysis was made. The difficulty of this method can be decreased greatly [1-2].

The application of correlation analysis method was very broad in data processing field. But traditional correlation coefficient or correlation function can only describe the whole correlation of the signal in the time domain. If one signal was affected by many signals, or interfered by colored noise obviously, the effect of the correlation analysis method was inferior. The wavelet analysis can extract the features of signals on different time and different frequency scales. The biggest problem is that the algorithm is very complicated to realize the extensive real time mining [3-9].

The supervisory information system (SIS) in the thermal power plant can save the whole operation data of the units. The SIS of a typical 600 MW unit can record 15000 points of data. So the massive data mining need a simple and effective method. Using the wavelet analysis idea for reference, a simple multi-frequency scale correlation analysis method was designed, which can revealed the interaction law of signals on different frequency scales, has clear physical significance, and suitable for extensive engineering application [2].

II. MULTI-SCALE FREQUENCY ANALYSIS METHOD

A. Filter Design

Using the wavelet analysis idea for reference, the decompose method of multi-scale filter on the frequency domain was deduced. The signal $x_0(s)$ can be decomposed as follows:

$$x_0(s) = G_0(s)x_0(s) + [1 - G_0(s)]x_0(s) \tag{1}$$

Let $x_{h1}(s) = [1 - G_0(s)]x_0(s)$;

$x_1(s) = G_0(s)x_0(s)$.

And then $x_1(s)$ can be decomposed sequentially as:

$$x_1(s) = G_1(s)x_1(s) + [1 - G_1(s)]x_1(s) \tag{2}$$

Let $x_{h2}(s) = [1 - G_1(s)]x_1(s)$;

$x_2(s) = G_1(s)x_1(s)$.

And then $x_2(s)$ can be decomposed similarly.

Let $x_{h(n+1)}(s) = [1 - G_n(s)]x_n(s)$;

$x_{n+1}(s) = G_n(s)x_n(s)$.

So,

$$x_{n+1}(s) = G_{n+1}(s)x_{n+1}(s) + [1 - G_{n+1}(x)]x_{n+1}(s)$$

$$n=0, 1\cdots \quad N \tag{3}$$

And $x_n(s)$ can be decomposed continually, finally we can get:

$$x_0(s) = x_{h1}(s) + x_{h2}(s) + x_{h(n+1)}(s) + x_{n+1}(s)$$

$$n=0, 1\cdots \quad N \tag{4}$$

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DOI 10.1109/CIS.2011.280

Where, choosing different $G_{\mathrm{n}}(s)$, different filter bank can be constructed, and $x_0(s)$ can be decomposed as different features. All the poles of $G_{\mathrm{n}}(s)$ must be stable. For example:

$$G_{\mathrm{n}}(s) = 1/(1+k^{\mathrm{n}}Ts)^{\mathrm{m}} \qquad n = 0,1,\cdots N \qquad (5)$$

Where, $k > 1$, m is positive integer. So $G_{\mathrm{n}}(s)$ is a low pass filter. The bigger the k is, the bigger the pace of the filter frequency scale is. The bigger the m is, the more approximate the constructed filter and the ideal filter are. The process of the signal decomposing was: (1) firstly the signal was decomposed into low frequency part and high frequency part; (2) then the low frequency part was further decomposed into relative low frequency part and relative high frequency part; (3) after n times decomposing, one low-pass filter, one high-pass filter and n band-pass filters were constructed as a filter bank.

Similar with the wavelet analysis, choosing suitable $G_{\mathrm{n}}(s)$, the change characteristics of signals on different frequency scale and different time scale can be observed. And the composing process is reversible.

B. Linear Correlation Analysis

In the specified period, the correlation coefficient and the correlation function between the signal $x(t)$ and $y(t)$ were defined as [10-12]:

$$\rho_{xy} = \frac{\int_0^T x(t)y(t)dt}{\sqrt{\int_0^T x^2(t)dt \int_0^T y^2(t)dt}} \qquad (6)$$

$$\rho_{xy}(\tau) = \frac{\int_0^T x(t)y(\tau+t)dt}{\sqrt{\int_0^T x^2(t)dt \int_0^T y^2(\tau+t)dt}} (\tau \in 0,T) \qquad (7)$$

Using the multi-scale frequency analysis method, firstly the signal $x(t)$ and $y(t)$ were decomposed by the multi-scale filters. And then the different frequency components of the signals were gained, which were $x_{\mathrm{h1}}(t)$, $x_{\mathrm{h2}}(t)$,$\cdots$, $x_{\mathrm{h(n+1)}}(t)$, $x_{\mathrm{n+1}}(t)$ and $y_{\mathrm{h1}}(t)$, $y_{\mathrm{h2}}(t)$, $\cdots$, $y_{\mathrm{h(n+1)}}(t)$, $y_{\mathrm{n+1}}(t)$. Finally the correlation coefficient or the correlation function between the components, such as between $x_{\mathrm{h1}}(t)$ and $y_{\mathrm{h1}}(t)$, $x_{\mathrm{h1}}(t)$ and $y_{\mathrm{h2}}(t)$, $x_{\mathrm{h2}}(t)$ and $y_{\mathrm{h1}}(t)$, $x_{\mathrm{h2}}(t)$ and $y_{\mathrm{h2}}(t)$ and so on, were calculated. Then the correlation coefficient $\rho_{x_{\mathrm{h1}}y_{\mathrm{h1}}}$ and $\rho_{x_{\mathrm{h1}}y_{\mathrm{h2}}}$, the maximum of the correlation function $\rho_{x_{\mathrm{h1}}y_{\mathrm{h1}}}(\tau)_{\max}$ and $\rho_{x_{\mathrm{h1}}y_{\mathrm{h2}}}(\tau)_{\max}$, and the time $\tau_{\max}$ were gained.

C. Characteristics Analysis

By analyzing the maximum of the correlation coefficient or the correlation function and the emerging time, the interaction between the signals and the characteristics were gained initially. The typical interaction relationship and the characteristics between the signal $x(t)$ and the signal $y(t)$ were:

- If the characteristics were low pass feature, the correlation coefficient between low frequency components was big and the correlation coefficient between high frequency components was small.
- If the characteristics were band-pass feature, the correlation coefficient between band-pass frequency components was big and the correlation coefficient between others frequency components was small.
- If the characteristics were pure delay feature, the maximum of correlation coefficient between most parts of frequency components was bigger and the emerging time of the maximum was consistent approximately.

III. APPLIED CASE

Using the method, the operation data of a 600MW unit in the thermal power plant were analyzed. According to equation 1-5, choosing $T = 10$, $k = 5$, $m = 2$, $n = 0,1$, two low pass filters with different cut-off frequency were constructed. And the signals were decomposed into low frequency component, intermediate frequency component and high frequency component. The furnace pressure signal and its related signals, such as boiler fuel flow, air flow, and the pressure of induced draft fan entrance, were analyzed by multi-scale frequency analysis method. The original signal, the low frequency component, intermediate frequency component and high frequency component of one set of results in analysis period were shown in figure1-figure2. The three sub-graphs in figure 1 were the furnace pressure signal, fuel flow signal, and the comparison between the low frequency component of the furnace pressure signal and the intermediate frequency component of the fuel flow signal. The two sub-graphs in figure 2 were the high frequency component of the furnace pressure signal and the low frequency component of the fuel flow signal. The fluctuation of furnace pressure increased on the condition of low fuel flow, and decreased on the condition of high fuel flow.

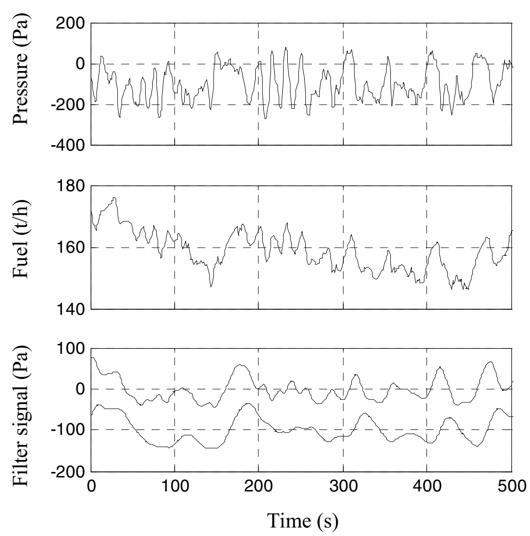

Figure 1. Contrast between the low frequency component of the furnace pressure signal and the intermediate frequency component of the fuel flow signal

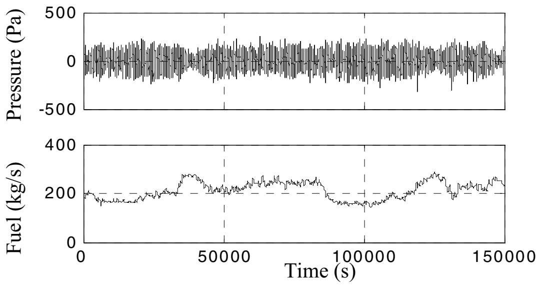

Figure 2. Contrast between the high frequency component of the furnace pressure signal and the low frequency component of the fuel flow signal

As shown in figure1- figure2, it was discovered that there was obvious correlation between the low frequency component and intermediate frequency component of the furnace pressure signal and the intermediate frequency component and high frequency component of the boiler fuel flow signal. The maximum of the correlation function were 0.86 and 0.72. The furnace pressure signal was an important safety parameter of boiler. The combustion control system maintained the boiler ventilation balance by controlling the furnace pressure. It was indicated by the operation routine and local experience that the majority of fault involved with combustion was accompanied by the abnormal furnace pressure. Some studies also indicated that the furnace pressure signal can reflect the change of the combustion state to some extent. The inner mechanism should be further analyzed.

IV. OBJECT MECHANISM ANALYSIS

The boiler was positive pressure direct firing pulverizing system and balanced ventilation design. Although the thermodynamic process of the combustion was very complicated, the process of combustion still followed the mass conservation law and energy conservation law as follows: [13-17]

$$dM/dt = q_{\mathrm{i}} - q_{\mathrm{o}} \tag{8}$$

$$dE/dt = Q_{\mathrm{i}} - Q_{\mathrm{o}} - Q_{\mathrm{f}} \tag{9}$$

Where M is the total mass of the air in the furnace (kg); q_{i} is the working medium flow into the furnace (kg/s); q_{o} is the working medium flow out of the furnace (kg/s); E is the total storage energy of the furnace air (MJ); Q_{i} is the fuel heat and the combustion heat (MW); Q_{f} is the absorption heat of the furnace heating surface (MW); Q_{o} is the heat carried by the working medium out of the furnace (MW).

The whole coal flow and the whole air flow into the furnace can be described as:

$$q_{\mathrm{i}} = K_1 u_{\mathrm{B}} \tag{10}$$

Where, K_1 is the amending coefficient; u_{B} is the whole fuel flow into the furnace (kg/s) .

The heat into the boiler furnace is:

$$Q_{\mathrm{i}} = K_2 u_{\mathrm{B}} \tag{11}$$

Where, K_2 is the conversion coefficient.

The heat out of the furnace can be described as:

$$Q_{\mathrm{o}} = q_{\mathrm{o}} c_{\mathrm{g1}} T \tag{12}$$

Where c_{g1} is the average specific heat of the gas flue in the furnace outlet (MJ/kgK) ; T is the temperature of gas flue in the outlet of the furnace (K) .

The absorption heat of the furnace heating surface can be described as:

$$Q_{\mathrm{f}} = K_3 (T_{\mathrm{hy}}^4 - T_{\mathrm{b}}^4) \tag{13}$$

Where, K_3 is the coefficient related to the blackness and the structure of the furnace; T_{hy} is the average temperature of the gas (K); T_{b} is the average temperature of the heating surface in the furnace (K).

The gas in the furnace can be approximately considered as ideal gas, and can be described as:

$$M = cpv / T_{\mathrm{hy}} \tag{14}$$

Where, p is the absolute pressure of the furnace (Pa); v is the whole volume of furnace (m^3); c is the coefficient of the state equation for the ideal gas, which is concerned only with the ingredients of the gas.

The stored energy of the gas flue in furnace was:

$$E = M c_{\mathrm{g2}} T_{\mathrm{hy}} \tag{15}$$

Where c_{g2} is the average specific heat of the gas flue in the furnace (MJ/KgK) .

The average temperature of the gas flue on a fixed load condition can be considered as:

$$T = K_4 T_{\mathrm{hy}} \tag{16}$$

Substituting equation 10 to equation 16 into the equation 8 and equation 9, and solving the partial derivatives, the equation 17 and the equation 18 can be gained as:

$$\frac{cv}{T}\frac{dp}{dt} - \frac{k_3 vp}{T^2}\frac{dT}{dt} = K_1 u_{\mathrm{B}} - q_{\mathrm{o}} \tag{17}$$

$$cc_{\mathrm{g}} v \frac{dp}{dt} = K_2 u_{\mathrm{B}} - q_{\mathrm{o}} c_{\mathrm{g}} T - K_3 (T^4 - T_{\mathrm{B}}^4) \tag{18}$$

Substituting equation 17 into the equation 16 and simplifying, the equation 19 can be gained as:

$$\frac{cc_{\mathrm{g}} vp}{T}\frac{dT}{dt} = K_2 u_{\mathrm{B}} - c_{\mathrm{g}} T K_1 u_{\mathrm{B}} - K_3 (T^4 - T_{\mathrm{B}}^4) \tag{19}$$

Whatever the control mode of the draught fan in large boiler was, the gas flue flow was adjusted by the inlet pressure of the draught fan finally. This part of simplified model can be described as:

$$q_{\mathrm{o}} = K_4 \sqrt{p - p_{\mathrm{o}}} \tag{20}$$

Where, K_4 is the resistance coefficient of the gas flue passage, air pre-heater and electrostatic precipitators; p_{o} is the inlet pressure of the draught fan. Substituting equation 20 into the equation 17, the equation 21 can be gained as:

$$cc_{\mathrm{g}} v \frac{dp}{dt} = K_2 u_{\mathrm{B}} - c_{\mathrm{g}} T K_4 \sqrt{p - p_{\mathrm{o}}} - K_3 (T^4 - T_{\mathrm{B}}^4) \tag{21}$$

The equation 19 and the equation 21 were the dynamic model of the furnace pressure and furnace temperature vs. fuel flow and induced draft fan inlet pressure. The model was constructed in the environment of MATLAB. The real boiler coal flow and the induced draft fan inlet pressure were introduced into the model, then the comparison between the model output and the real output was shown in figure 3. As shown in figure 3 the bold line was model output curve and the thin line was the real boiler output curve. The four sub-graphs in figure 3 were the fuel flow signal, forced air flow pressure signal, furnace pressure signal and the furnace temperature signal. Because there was no measuring point of the furnace average temperature in boiler, the trend of the real average temperature can be observed by referring the flue gas temperature of deflecting chamber in boiler. The high frequency noises were removed from the furnace pressure signal by the low pass filter. As shown in figure 3 the model output can basically reflect the change of the real signal.

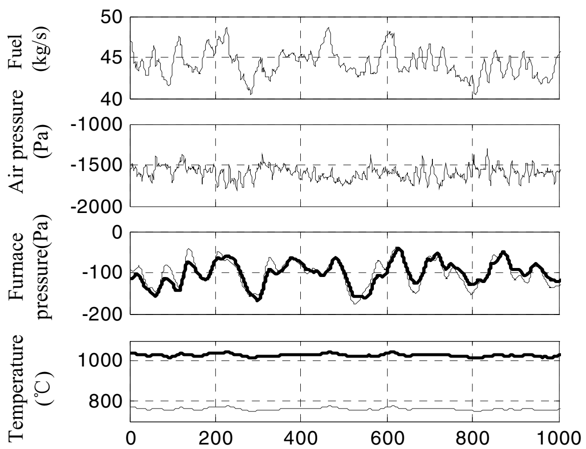

Figure 3. Model verification

V. OBJECT CHARACTERISTICS ANALYSIS

Because of the multi-variable and the nonlinearity of the object, it was difficult to solve the differential equation. Adopting the frequency domain analysis method of classical control theory, the object was analyzed in the environment of MATLAB.

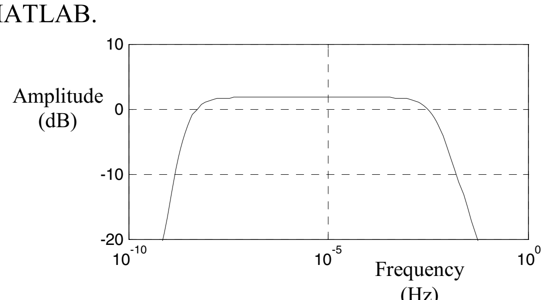

Figure 4. Amplitude frequency characteristics curve of the furnace temperature vs. the furnace pressure

The furnace pressure was usually controlled by the draught fan flow of the boiler in thermal power plant. For the model, the furnace pressure was controlled by the draught fan inlet pressure. Introducing the inertia of the actuator, designing the PID control loop, the amplitude frequency characteristics curve of furnace temperature vs. furnace pressure was observed by simulation. It was shown in figure 4 that there was a band-pass feature between the furnace temperature and the furnace pressure, which was consistent with the first conclusion of the multi-scale frequency analysis. The result shows that the furnace pressure can reflect the change of the furnace temperature in the large scope of frequency.

The furnace average temperature or the outlet temperature of furnace was very important state variable in the thermal power units, which affect lots of parameters, such as unit load, throttle pressure, superheated steam temperature and drum water level, and the distribution proportion of the radiation heat and the convection heat. But the proportion of the radiation heat and the convection heat can not be measured directly. The method described above can observe the change of the furnace temperature indirectly, and can provide the support for the control optimization, fault diagnosis and so on.

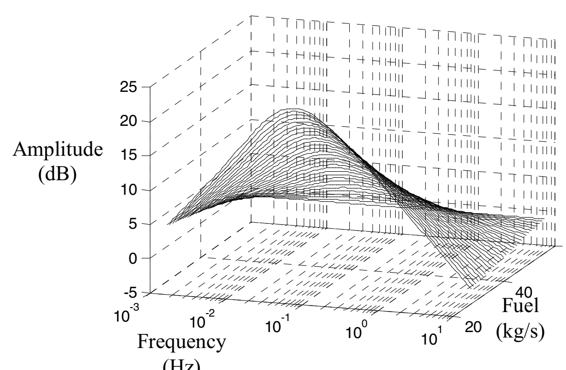

Figure 5. Amplitude frequency characteristics curve of the boiler fuel flow vs. the furnace pressure

By changing the operation point of the furnace temperature and the furnace pressure, the amplitude frequency characteristics curves of the boiler fuel flow vs. the furnace pressure and the furnace temperature on different operation point were observed. It was shown as figure 5 that the lower the boiler fuel flow was, the bigger the gain of the boiler fuel flow vs. the furnace pressure and the furnace temperature was. The results show that the same change of the fuel flow on the low load condition will lead to bigger change of the furnace pressure, which was consistent with the second conclusion of the multi-scale frequency analysis. The fluctuation of the furnace pressure became bigger on the low load condition, which was caused by the strong nonlinearity of the object. And the strong nonlinearity of the object also was the reason that the furnace pressure and the drum water level on low load condition were difficult to control.

VI. Conclusions

Using the wavelet analysis idea for reference, the multi-scale filter was designed to decompose the signals into different frequency scale components, and then the linear correlation analysis between the components was gained. The results show that the furnace pressure can reflect the feature information of the combustion state in boiler. The conclusions were gained by the mechanism analysis as follows:

- The furnace pressure signal can reflect the change of the furnace average temperature in the large scope of the frequency.
- The fluctuation of the furnace pressure and the furnace temperature on low load conditions became bigger, and the combustion state became worse, which was caused by the nonlinearity of the object itself.

Acknowledgment

The project of the presented paper was supported by the Fundamental Research Funds for the Central Universities (11QG73) and the Ph. D. Programs Foundation of Ministry of Education of China (200800790006).

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