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THE BALANCE OF THE AIR FLOW NOISE IN EXTRACTING ACOUSTIC SIGNALS OF THE CRACKED BLADE

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The blade fault is a very serious problem; recently, the acoustic method has achieved a great success in exploring the crack developing. Synchronization time averaging is a key technique, which was used to eliminate white noise; in the de-noise the effects of the load change is still a problem to be solved. The effect of the unstable flow will have some bad influence on the results averaged. In order to eliminate the bad influence, a symmetrical decomposition method has been discussed for de-noising in a symmetrical container in this paper. The main goal is trying to convert an unstable problem into a relative stable problem. In this method the noise signal of the symmetrical section has been decomposed at the symmetrical base, then the noise signal measured will be balanced with the symmetrical terms; the symmetrical terms are relatively stable, the unbalanced blade signal will be enhanced. The sensor position has been determined to get an optimized result, in this way the signal-to-noise ratio has been improved and the effects of the flow disturbance have been avoided.

1. INTRODUCTION

Under the action of fatigue and stress concentration, a crack would appear in blades, and the cracked blade would be broken as the crack propagates, so the blade state has attracted a lot of attention for years. Several methods, based on different principles, have been developed in an attempt to explore the blade condition when it is working. Among them, we consider three main methods. The first one is non-contacting measurement of the vibrating displacement; the blade condition will be judged by decoding the vibrating displacement signal of the blade tip, it was developed firstly by the Central Research Institute of Aeronautical Engine of former U.S.S.R. [1]. The second method is Infrared thermal measurement which monitors temperature changes in the cracked blade area with Infrared pyrometer [2–4]. The third is acoustic measurement of the blade vibration; it judges the blade condition through the acoustic signals emitted by the blades. Important progress was made by Liberty Technology Center, Inc., and Electric Power Research Institute (EPRI) of U.S.A., which developed a STARS system (Steam Turbine Acoustic Response System) [5, 6]. The cracks were identified by detecting the resonant events which occurred when the blade natural frequency, with the crack growth, shifted into coincidence with an integer multiple of working speed. The de-noising is the key technique of this method; the time history average is adopted to eliminate the masking noise, based on the facts that the flow noise is nearly white noise and its expected value is zero. In order to get enough accuracy, more than hundred thousands of samples were acquired and the acquiring procedure takes

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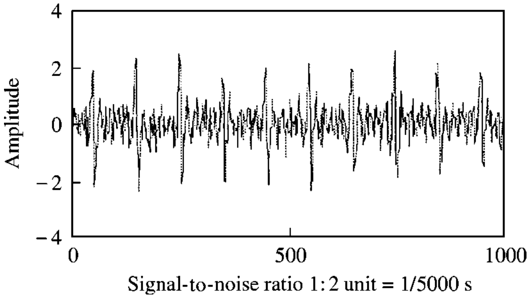

Figure 1. Signals averaged 200 times for *S*/*N* ratio 1:2.

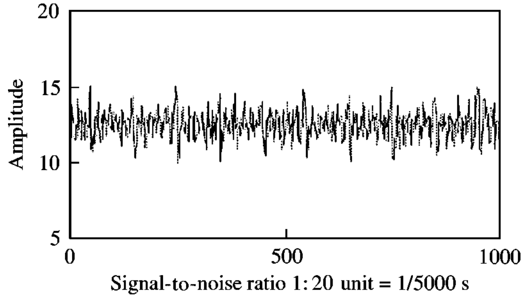

Figure 2. Signals averaged 200 times for *S*/*N* ratio 1:20.

nearly half an hour in STARS system. So when the blades work in the states of starting up or shutting down or increasing loads, the changes will exert some bad influence on the averaged results. What we want to do here is to attempt to find a way to realize the goal of de-noising and to eliminate the unstable flow influence.

2. DE-NOISING BY SYNCHRONOUS TIME AVERAGING

The acoustic signal in the engine is very complicated and is emitted by blades, working media and structure. In order to pick the blade sound out of the others, the character of the acoustic signal has to be studied carefully. From the view of the frequency domain the noise has wide frequency band, the blade acoustic signal modulated by Doppler effects has wide frequency band as well, the structure noise is related to working frequency and its integer multiple. Due to the mutual frequency overlap, the frequency analysis is hard to divide them separately, so the STARS adopts synchronous time averaging to reduce the steam flow noise. Figure 1 shows the result of a signal averaged 200 times, in this case the signal-to-noise ratio is 1:2 and there is only one noise. Figure 2 shows the result of a weak signal averaged 200 times; in this case the signal-to-noise ratio is 1:20 and there are two noises with non-zero means. The result shows that averaging 200 times is not enough to get rid of the noise effects, so average was taken hundred thousand times and the acquiring procedure takes nearly half an hour in STARS system. If the working state is unstable it will bring more problems at the synchronous time-averaging.

3. DE-NOISING IN A SPECIAL SYMMETRICAL CONTAINER

As stated, the method of extracting blade signal from the noise, which masks it, is the key of de-noising; synchronous time averaging reduces noise based on the fact that white noise has zero expected value, but the disturbance of the steam flow may cause unexpected effects on the mean so that the blade signal is hard to be extracted from the noise.

The basic idea is that the measured values of signal at two sensors apart in the noise field are correlative if the signals come from the same noise emitter. If the signals come from many random noise emitters, which is statistic symmetry, these measured values of signal are also correlative. We can always find two points at which the noise expected value is nearly the same; these points could be called symmetric points. Making use of the fact that the noise level is nearly the same at two symmetric points, the blade signal could be got by subtracting noise signal from the measured signal. Due to the correlativeness the statistical expected value is relatively stable between two symmetric points, the averaging times could be decreased and the unstable effects could be minimized Then the disadvantage of the synchronous time averaging can be overcome. If the blades are in a symmetric structure container and the flow noise is statistic symmetrical, the method stated above could be used to deal with the signal measured.

Statistic symmetry means that if there are a number of noises their contribution at two symmetric points is the same, if there are two noises their contribution at two symmetric points *a* and *b* could be expressed, respectively as

$$Contri_{\mathrm{A}} = N_1(t)f_1(a) + N_2(t)f_2(a), \qquad Contri_{\mathrm{B}} = N_1(t)f_1(b) + N_2(t)f_2(b). \tag{1}$$

Taking the expected means of $Contri_{\mathrm{A}}$ and $Contri_{\mathrm{B}}$ we get

$$E(Contri_{\mathrm{A}}) = E(N_1(t)f_1(a) + E(N_2(t))f_2(a) \quad \text{and} \quad E(Contri_{\mathrm{B}})$$
$$= E(N_1(t))f_1(b) + E(N_2(t))f_2(b).$$

If the statistical symmetrical condition were satisfied, the $E(Contri_{\mathrm{A}})$ should be equal to $E(Contri_{\mathrm{B}})$. It means $E(N_1(t))f_1(a) + E(N_2(t))f_2(a) - E(N_1(t))f_1(b) - E(N_2(t))f_2(b) = 0$ then

$$E(N_1(t))(f_1(a) - f_1(b)) = E(N_2(t))(f_2(b) - f_2(a)). \tag{2}$$

The above formula (2) means that noise $N_1(t)$ and $N_2(t)$ should have zero expected value or should be symmetric and have the same statistical characters. The latter conclusion will be advantageous in dealing with the de-noising. Due to the noise expected mean being correlative at individual points of a symmetric section, the distribution function of noise at a symmetric section of a symmetric structure can be expanded by Taylor series at symmetric conditions. Assume that the distribution function at a special section is

$$EX(r, \theta, t) = f(r, \theta, \alpha, \beta, \ldots, t). \tag{3}$$

Here r is the radius vector, θ is radius angle, $\alpha, \beta, \ldots$ represent the relative factor which affect the acoustic distribution. Expanding the function by Taylor series at symmetric condition of $\alpha_0, \beta_0, \ldots$ etc., we get

$$EX(r, \theta, t) = f(r, \theta, \alpha_0, \beta_0, \ldots, t) + \frac{\partial f(r, \theta, \alpha_0, \beta_0, \ldots, t)}{\partial \alpha}\mathrm{d}\alpha + \frac{\partial f(r, \theta, \alpha_0, \beta_0, \ldots, t)}{\partial \beta}\mathrm{d}\beta + \ldots. \tag{4}$$

Here α_0 and β_0 are the symmetric condition values of α, β. Let $EX_0(r, \theta, t) = f(r, \theta, \alpha_0, \beta_0, \ldots, t)$ represent symmetric terms of the noise distribution function at a defined section, let

$$\mathrm{d}X(r, \theta, t) = \frac{\partial f(r, \theta, \alpha_0, \beta_0, \ldots, t)}{\partial \alpha} \mathrm{d}\alpha + \frac{\partial f(r, \theta, \alpha_0, \beta_0, \ldots, t)}{\partial \beta} \mathrm{d}\beta + \ldots$$

represent the disturbed terms around the symmetric terms of the noise distribution function at a defined section. In this sense, the noise distribution function becomes

$$EX(r, \theta, t) = EX_0(r, \theta, t) + \mathrm{d}X(r, \theta, t) \tag{5}$$

If we can substract the symmetric component $EX_0(r, \theta, t)$ from noise signal $EX(r, \theta, t)$ the effects of the noise will be reduced, the effect of the flow disturbance could be under control. Considering the term $\mathrm{d}X(r, \theta, t)$ is generated by non-symmetric factors of the symmetric section, compared with the symmetric component $EX_0(r, \theta, t)$ term, it is a high order term.

3.1. BLADE SIGNAL

For the cylinder shown in Figure 3, when the air flows in the left-hand side and crosses the blades out of the right side, $Sig_m(r, \theta, t)$ the signal measured at the symmetric section can be expressed as

$$Sig_m(r, \theta, t) = Sig_n(r, \theta, t) + Sig_b(r, \theta, t) \tag{6}$$

Here $Sig_n(r, \theta, t)$ is noise signal, $Sig_b(r, \theta, t)$ is blade signal. Due to the Doppler effects $Sig_b(r, \theta, t)$ the blade signal is a non-symmetric distribution signal.

3.2. STRUCTURE VIBRATION SOUND

The structure vibration emits sound and its frequency is the same as that of structure vibration. Even the section is symmetric due to the difference of the rigid structure along the X and Y directions, there exist the zero vibration points, the acoustic function of the structure vibration is axial symmetry. Decomposing the structure acoustic signal $Sig_s(r, \theta, t)$ at axial symmetric condition we get

$$Sig_s(r, \theta, t) = ES(r, \theta, t) + \mathrm{d}S(r, \theta, t), \tag{7}$$

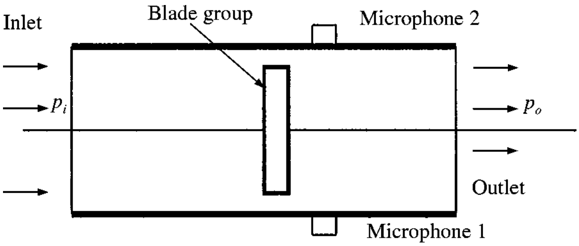

Figure 3. Symmetric structure.

where $ES(r, \theta, t)$ express the symmetric function of the structure sound at point(r, θ), then

$$ES(r, \theta, t) = ES(r, \pi - \theta, t). \tag{8}$$

$dS(r, \theta, t)$ is deviation caused by those non-symmetric factors, such as the mutual action between air flow, structure and blades.

3.3. BLADE SIGNAL EXTRACTING

As in the analysis above, the acoustic signal in the position (r_1, θ_1) can be expressed as

$$Sig_m(r_1, \theta_1, t) = Sig_b(r_1, \theta_1, t) + Sig_n(r_1, \theta_1, t) + Sig_s(r_1, \theta_1, t). \tag{9}$$

Averaging the signal measured $Sig_m(r_1, \theta_1, t)n$ times, its expected value could be expressed as

$$E(Sig_m(r_1, \theta_1, t)) = E(Sig_b(r_1, \theta_1, t)) + E(Sig_n(r_1, \theta_1, t)) + E(Sig_s(r_1, \theta_1, t)). \tag{10}$$

As the blade vibration is relatively stable $E(Sig_b(r_1, \theta_1, t) = Sig_b(r_1, \theta_1, t)$, the structure vibration is also stable $E(Sig_s(r_1, \theta_1, t)) = Sig_s(r_1, \theta_1, t)$, the noise term could be decomposed in mean term and in deviation term, $E(Sig_n(r_1, \theta_1, t)) = EN_0(r_1, \theta_1, t) + dN(r_1, \theta_1, t)$. The result of averaging the signal n times could be expressed as

$$E(Sig_m(r_1, \theta_1, t)) = Sig_b(r_1, \theta_1, t) + Sig_s(r_1, \theta_1, t) + EN_0(r_1, \theta_1, t) + dN(r_1, \theta_1, t). \tag{11}$$

Based on the concept of symmetric decomposition de-noising we could also get the results at symmetric point (r_1, θ_2) as

$$E(Sig_m(r_1, \theta_2, t)) = Sig_b(r_1, \theta_2, t) + Sig_s(r_1, \theta_2, t) + EN_0(r_1, \theta_2, t) + dN(r_1, \theta_2, t). \tag{12}$$

As the structure vibration sound is the same at symmetric points and the noise expected value at symmetric points is the same, the difference between two symmetric points is

$$\begin{aligned} E(Sig_m(r_1, \theta_1, t)) - E(Sig_m(r_1, \theta_2, t)) &= Sig_b(r_1, \theta_1, t) - Sig_b(r_1, \theta_2, t) \\ &\quad + dN(r_1, \theta_1, t) - dN(r_1, \theta_2, t). \end{aligned} \tag{13}$$

If we could get maximum value of the term $Sig_b(r_1, \theta_1, t) - Sig_b(r_1, \theta_2, t)$, then we could reduce noise and raise signal–noise ratio; for single blade case the best symmetric positions are the points at symmetric axis; in this case when the defined blade approaches sensor A, the signal measured at sensor A has maximum value, while the signal measured at sensor B has the minimum value, the two sensors are 180° apart.

If there are a number of blades considering the mutual overlapping effects of blade signals on sensors, the sensor symmetric distance along the circle should be the third of the circle angle of two neighbor blades.

3.4. IDENTIFICATION OF THE BLADE FAULTS

The purpose of extracting blade signal is to analyze the blade state, so the response trend curve of each blade has to be made from the measured signals. In the normal state the response amplitude of each blade has only slightly changed around its expected value, but in the fault states the response amplitude of each blade has sharply changed or jumped which we call resonant event. Through checking the unusual changes on the response trend curve of each blade, we could judge whether the blade is in good or in bad condition, meanwhile we could estimate the crack propagating state by the jumping times.

4. NUMERICAL SIMULATION

In this part an attempt is made to test the efficiency of the symmetric decomposition de-noising. In the system as shown in Figure 3, assume that the flow noise is a random variable of time t. In order to get an optimized monitoring effect of blade vibration, we define the angle of two sensors A and B along circle as the third of the circle angle of two neighbor blades and we assume that there are four noise emitters which are located symmetrically, and there is more than one blade such as four blades on the blade wheel. Figure 4(a) shows blade acoustic signal which is generated artificially at A point, Figure 4(b) shows noise signal which is generated by random function *rand*(4, 1000) of MATLAB at A point, from the scale of Figure 4, we can see that the signal-to-noise ratio is around 1/20, the blade signal is masked by the noise.

Figure 5 shows the results of composed signal that is averaged 200 times; in this case, the angle of sensor A to sensor B is 30°. Figure 5(a) shows the results averaged at sensor A. Figure 5(b) shows the results averaged at sensor B.

Figure 6(a) shows the signal obtained by subtracting the signal in Figure 5(b) from that in Figure 5(a), Figure 6(b) shows the signal obtained after some overlapped terms have been eliminated from the signal in Figure 6(a). Compared with Figures 5 and 4(a), the result in Figure 6(b) is much improved. Even if there is a little difference, this difference is due to the contribution of other blades, the style of the vibrating wave form remains the same. The averaging times have been reduced and the unstable effects of flow have been overcome. Figure 7(a) shows time history signal of blade 3 extracted from the signal in Figure 6(b), and

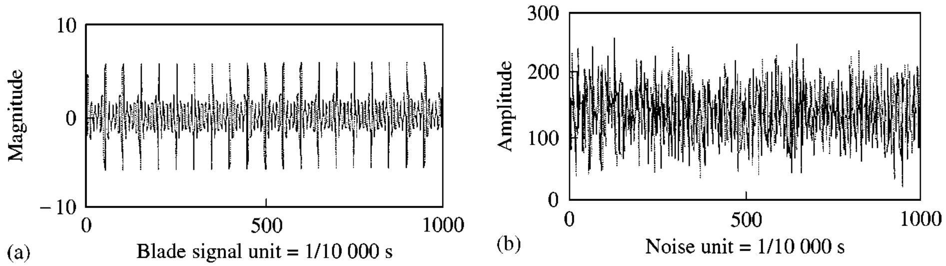

Figure 4. (a) Blade vibrating acoustic signal; (b) noise signal.

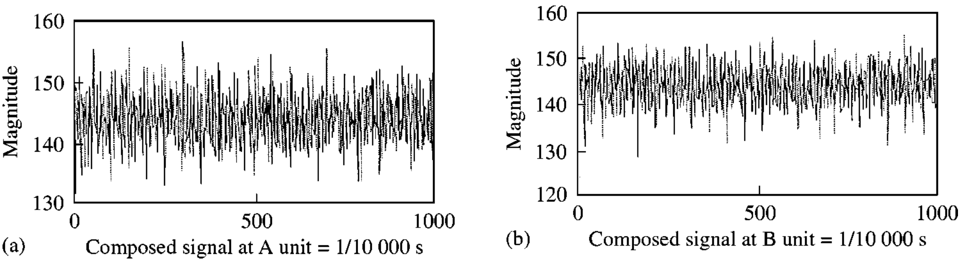

Figure 5. (a) Composed signal at sensor A; (b) composed signal at sensor B.

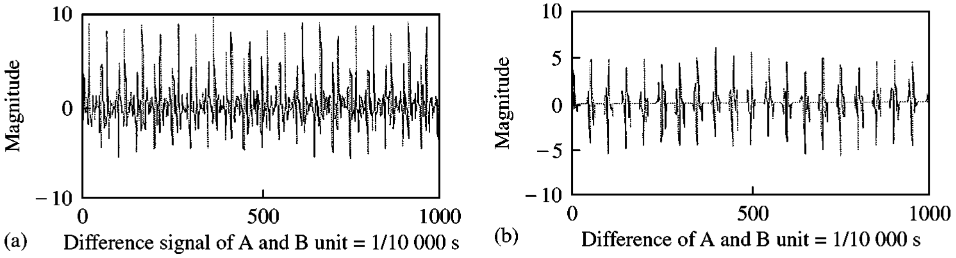

Figure 6. (a) Untreated signal; (b) treated signal.

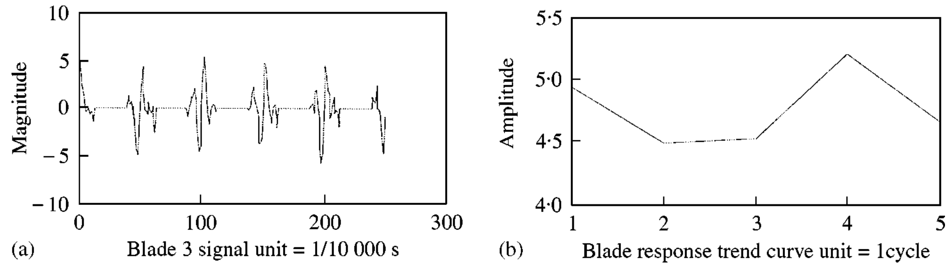

Figure 7. (a) Time history signal of blade 3; (b) response trend curve of blade 3.

we could get response trend curve of blade from the signal in Figure 7(a) as shown in Figure 7(b). The condition for each blade can be judged by the resonant events and by the wave tumble on its trend curve. If there were some jumps appearing on the trend curve, it means that the crack is developing. If the trend curve had some unusual changes, something might be going wrong with the blade other than crack. If there were several cracked blades, the case will be quite complicated; in order to making correct judgment, we need a waterfall map consisting of trend curves of all blades. Based on the consideration that the contribution of cracked blade on its own trend curve is much bigger than that on other trend curves, compared with the changes on its own trend curve and the changes between trend curves, we can judge which blade has something wrong with it.

5. CONCLUSION

Comparing Figure 6(b) with Figures 4(a) and Figure 5, we can see that the method is quite effective, saves computer times and overcomes the trouble caused by working media disturbance. Since this method is based on the fact that the noise signals at A and B come from the same noise emitters which have statistic symmetry, if the statistic symmetric condition were broken the method would not get expected results. The optimized position of sensors requires further study.

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