Data Zeroing Based on Correlation and Linear Interpolation of the Blade Tip-Timing Data

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***Abstract*—The blade tip-timing has become the most promising technique in the field of rotating blade vibration monitoring with its advantages of non-contacting. However the signal can be disturbed by many factors, especially the noise and drift of the blade vibration displacement curve caused by the centrifugal force changed with rotating speed. The main difficulty to data zeroing is to prevent the peak amplitude from being attenuated or eliminated. In this paper, a method was developed using blade vibration displacement to identify the areas of resonance by calculating the correlation of the data over a number of assembly revolutions from the multi-probe. The blade vibration simulator is carried out to study the relationship between the number of probes and the window width in the correlation. Applying this method into the experimental data, and verify the superiority of the correlation method.**

Keywords-blade tip-timing; data zeroing; multi-probe correlation; linear interpolation

I. INTRODUCTION

BTT is a non-contacting and non-intrusive measurement technology that gathers data about the dynamic behaviour of a rotating bladed assembly by recording the arrival times of each blade tip under a number of probes fixed to the assembly casing. The arrival times can be converted into displacement using the speed of the rotor and its radius at each probe. Processing and analysis of this data can yield information on the vibration characteristics of each blade [1].The theory chart of the tip-timing system [2] are shown in Fig.1.

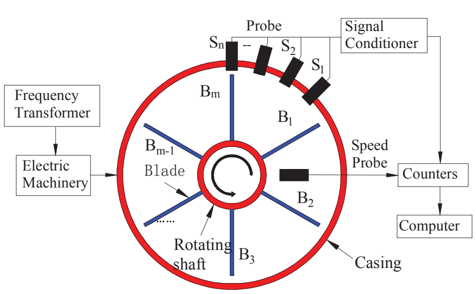

Figure 1. Blade tip-timing system

Zero drift refers to the phenomenon that the vibration displacement curve of the blade is far from the zero reference line. The influence of the aerodynamic load on the measured data is mainly a slow deviation from the balance position of the blade, which is mainly related to the rotational speed, the blade configuration and the airflow. Therefore, it is an indispensable operation to data zeroing before analyzing the blade vibration data. Russhard [3] proposed a method by carrying out a revolution-by-revolution cross correlation of the probe data. The Tianjin University [4] adopts the drift calibration method to data zeroing which is multi-point averaging in the form of sliding window and calculate the difference between the measured data and the zero-drift reference to achieve it. The drift calibration method requires the size of the sliding window much larger than the number of points on the engine order, but the large sliding window size will reduce the confidence in both amplitude and phase for synchronous responses which leads to the inaccuracy of algorithms.

Therefore, in order to eliminate the influence of the drift calibration method, a method was developed using the correlation of the data based on the Russhard's method, and proposed the form of the sliding window to calculate correlation. Finally, the linear interpolation is used to obtain the zero-drift curve.

II. THEORY ON THE CORRELATION METHOD

The BTT data measured by all the probes are the vibration displacements of the same blade in the same period. The only difference is that the installation angles of different probes are different, resulting in different phases. By calculating the cross-correlation between data of different sensors in the same period, it is possible to find the underlying characteristics at the time of resonance. When the measured signal consists of no noise, the correlation is always 1. Hence the correlation method can be used to find the resonance.

The BTT data measured can be expressed as (1):

$$y_{ns} = x_{ns} + e_{ns} \tag{1}$$

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where y_{ns} is the single blade data measured at probe s on rotation n . where $n = 1,2,3\ldots$. x_{ns} is the definite components while e_{ns} is the measurement noise.

The multi-probe correlation- X_r is shown as follows [1]:

$$X_r = \frac{2\sum_{s=1}^{P} y_{ns} y_{(n+1)s}}{\sum_{s=1}^{P} y^2{}_{ns} + \sum_{s=1}^{P} y^2{}_{(n+1)s}} \tag{2}$$

where y_{ns} is single blade data measured at probe s on rotation n. P is the number of probes. Submit (1) to (2):

$$X_r = \frac{2\left[\sum_{s=1}^{p} x_{ns}x_{(n+1)s} + \sum_{s=1}^{p} x_{ns}e_{(n+1)s} + \sum_{s=1}^{p} e_{ns}x_{(n+1)s} + \sum_{s=1}^{p} e_{ns}e_{(n+1)s}\right]}{\sum_{s=1}^{p}\left(x_{ns}+e_{ns}\right)^2 + \sum_{s=1}^{p}\left(x_{(n+1)s}+e_{(n+1)s}\right)^2} \tag{3}$$

Because e_{ns} is symmetric with respect to 0, so $\sum_{s=1}^{p} x_{ns}e_{(n+1)s} \to 0$, $\sum_{s=1}^{p} x_{(n+1)s}e_{ns} \to 0$, $\sum_{s=1}^{p} e_{(n+1)s}e_{ns} \to 0$, $\sum_{s=1}^{p} x_{ns}e_{ns} \to 0$, $\sum_{s=1}^{p} x_{(n+1)s}e_{(n+1)s} \to 0$. Equation (3) can be transformed:

$$X_r = \frac{2\sum_{s=1}^{p} x_{ns}x_{(n+1)s}}{\sum_{s=1}^{p}\left(x_{ns}{}^2 + e_{ns}{}^2\right) + \sum_{s=1}^{p}\left(x_{(n+1)s}{}^2 + e_{(n+1)s}{}^2\right)} \tag{4}$$

According to (4), $x_{ns} \approx x_{(n+1)s}$, when the blade resonates, the amplitude and phase of adjacent revolutions are basically the same. The definite components x_{ns} is much larger than the random components e_{ns} . At this time, the correlation would be close to 1. When the blade does not resonate, the amplitude of definite components x_{ns} would be much lower, so the influence of random components e_{ns} will lower the correlation result.

Considering the difference in the installation position of the probe, zero drift of the blade displacement measured by each probe is different. In order to eliminate this effect, improve (2) can get:

$$X_r = \frac{2\sum_{s=1}^{P}\left(y_{ns} - \frac{1}{p}\sum_{s=1}^{P} y_{ns}\right)\left(y_{(n+1)s} - \frac{1}{p}\sum_{s=1}^{P} y_{(n+1)s}\right)}{\sum_{s=1}^{P}\left(y_{ns} - \frac{1}{p}\sum_{s=1}^{P} y_{ns}\right)^2 + \sum_{s=1}^{P}\left(y_{(n+1)s} - \frac{1}{p}\sum_{s=1}^{P} y_{(n+1)s}\right)^2} \tag{5}$$

The continuous revolutions is defined as a sliding window. Window width of 1 means one revolution of data, and window width of 2 means two revolutions of data. Sliding window can reduce the effect of noise to highlight the definite components, which is beneficial to the calculation of correlation. The window is moved by changing the value of *n*, and this process is defined as a sliding window. Equation (5) can be transformed into (6).

$$X_r = \frac{2\sum_{s=1}^{P}\left(\overline{y}_{ns} - \frac{1}{p}\sum_{s=1}^{P} \overline{y}_{ns}\right)\left(\overline{y}_{(n+1)s} - \frac{1}{p}\sum_{s=1}^{P} \overline{y}_{(n+1)s}\right)}{\sum_{s=1}^{P}\left(\overline{y}_{ns} - \frac{1}{p}\sum_{s=1}^{P} \overline{y}_{ns}\right)^2 + \sum_{s=1}^{P}\left(\overline{y}_{(n+1)s} - \frac{1}{p}\sum_{s=1}^{P} \overline{y}_{(n+1)s}\right)^2} \tag{6}$$

where $\overline{y}_{ns}$ is the mean blade signal of the blade data at probe *s* on rotation *n* and *k* revolutions next to each other. The *2k+1* is the window width.

The correlation can reach values of -1 to 1. Correlation close to 1 indicates the resonance. Generally, 0.85 is recommended as the threshold. The correlation above the threshold is considered to be the resonance, vice versa. The correlation method can identify the resonance peak of synchronous vibration for further parameter identification. Using linear interpolation for the data zeroing in the synchronous vibration.

For data outside the resonance using moving average [5], the expression is:

$$y_k{}' = \frac{1}{2n+1}\sum_{k=m-n}^{m+n} y_k \tag{7}$$

where $y_k{}'$ represents the blade vibration displacement after moving average, y_k represents the raw displacement where $m = n+1, n+2 \ldots N-n \ldots 2n+1$. *2n+1* represents the range of the local sliding average. When *n*=2, it is the five-point moving average, *k* is the center point of the moving average, and *m* is the value range of the moving average. Too many data points in the moving average would lower resonance peaks and lead to phase shifts , which would affect the result of parameter estimation. Considering the moving average in the zero drift only needs to obtain the offset tendency of the blade displacement. In the following experiment, a five-point moving average was selected.

This method uses a sliding window to calculate the multi-probe correlation indicates possible integral engine order vibration events.

III. SIMULATION

According to the principle of correlation method, it is necessary to calculate the correlation of blade vibration data related to multiple probes in the form of sliding window. In the present paper, the simulation is mainly used to illustrate the method and investigate the influence of window width.

Based on the graphical simulation platform Simulink in Matlab, A six blades vibration model was established to yield the BTT signal [6]. Assuming that no coupling occurred between the six blades, the blade natural frequency was 180 Hz. Four tip timing sensors with mounting angles of 0°, 25°, 50°, 75° were distributed on the casing. Variable speed frequency ran up from 81Hz to 100Hz. Running the simulator and implant exponential zero drift . 30% Gaussian white noise was added to the signal simulator, so the vibration displacement as shown in Fig.2.

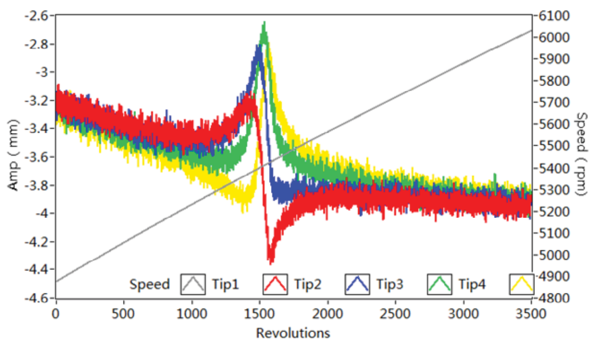


Figure 2. Vibration displacement curve with zero drift

This experiment used the simulation data, window width were taken as 1, 2, 3, and 4, using three probes signals and four probes signals into calculate the correlation curves. The specific steps to data zeroing are as follows.

A. Choose the window width

Select the probes that participate in correlation calculations. and determine the window width. However, the window width should not be too large, 1~4 revolutions will be fine.

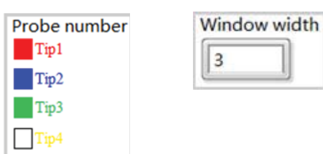


Figure 3. Choose the parameters

B. Calculate the correlation

After selecting the window width, use (6) to calculate the correlation curve. Identify resonance by the correlation threshold. The continuous data segment which the correlation always above the threshold is considered to be resonance, vice versa. The continuous data segment with correlation >0.85 calculated in the Fig.4 is 1527~2553.

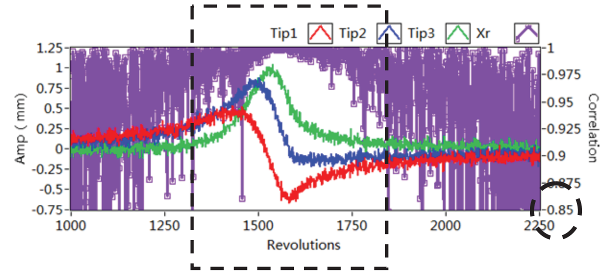


Figure 4. Correlation curve

C. Linear interpolation

Where a resonance is identified, then a linear interpolation of the values is carried out between the start (Revolution 1527) and the end (Revolution 2533) of the identified integral engine order event for the zeroing to be applied [7]. For data outside the identified areas of activity, moving average is utilized.

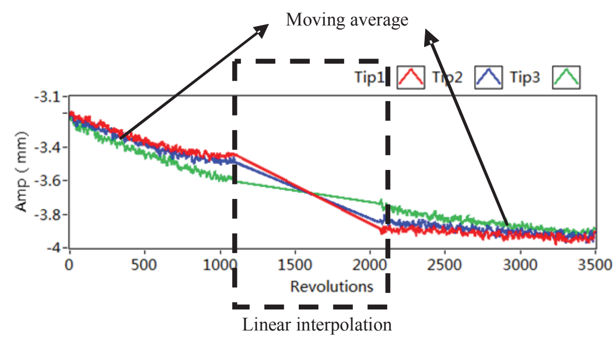


Figure 5. Get the zero drift line

D. Data zeroing

Finally, the zero-drift curve can be subtracted from the blade vibration curve to complete the data zeroing of the blade tip timing signal.

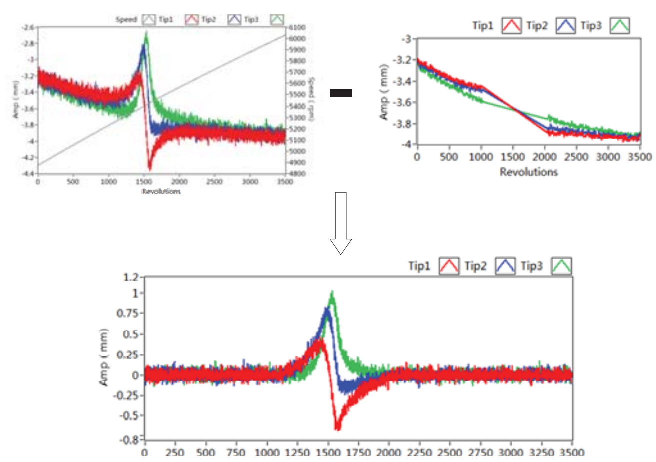
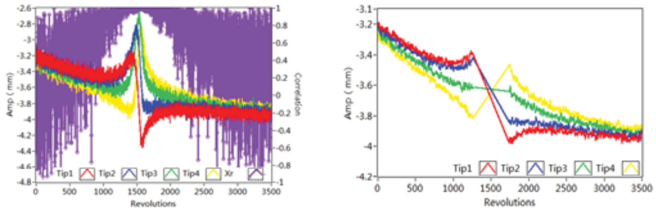
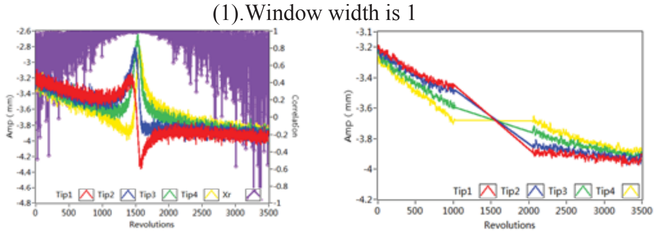


Figure 6. Data zeroing results

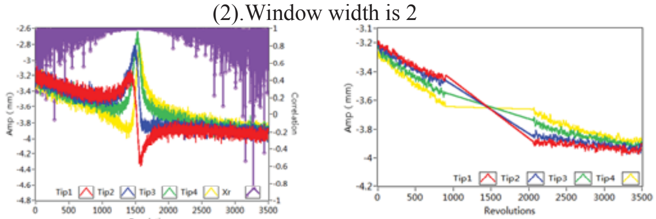
Fig.7 shows the correlation calculation results and the zero-drift curves of different window widths when the number of probes is 4. The continuous data segments with the correlation >0.85 are 1261~1745, 1027~2053, 899~2065 and 822~2334. As the window width increases, the zero-drift curve becomes more and more smooth.



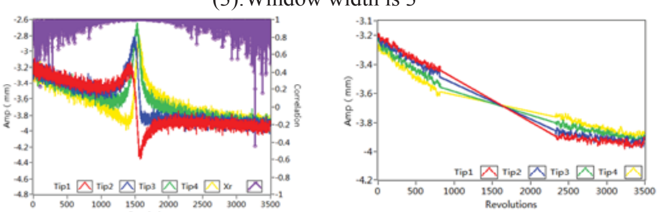
(1).Window width is 1



(2).Window width is 2



(3).Window width is 3



(4).Window width is 4

Figure 7. The number of probes is 4, the correlation results under different window widths

Finally, compare the peak-to-peak value of the simulated signal before and after data zeroing. The comparison results are shown in Table. I . The peak-to-peak value refers to the difference between the signal peak and the valley in one cycle which describes the range of the signal value variation.

TABLE I. THE COMPARISON OF PEAK-TO-PEAK VALUE 'S RELATIVE ERROR BETWEEM THE EFFECT OF WINDOW AND THE NUMBER OF PROBES

Probe numbers		Window width			
		1	*2*	*3*	*4*
Three	***Tip1***	33.25%	10.96%	3.32%	2.92%
	Tip2	46.08%	8.61%	2.38%	2.09%
	Tip3	35.12%	5.98%	2.18%	1.10%
Four	***Tip1***	12.68%	2.90%	2.57%	1.33%
	Tip2	8.81%	2.22%	1.89%	0.73%
	Tip3	4.94%	1.41%	1.34%	1.40%
	Tip4	14.30%	2.97%	2.80%	1.26%

Comparing Table. I , the following conclusions can be drawn:

(1). When the number of probes is constant, the relative error of the peak-to-peak value gradually decreases as the window width increases.

(2). When the window width is constant, the more the number of probes, the smaller the relative error of the peak-to-peak value, the zero drift effect will be better.

Fig.8 shows the comparison of the zero-drift curve between the correlation method and the drift calibration method with a window width of 200.

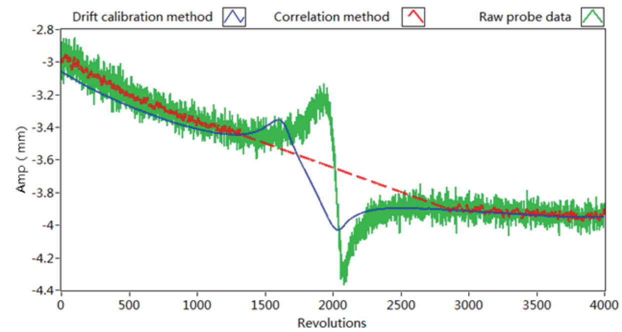
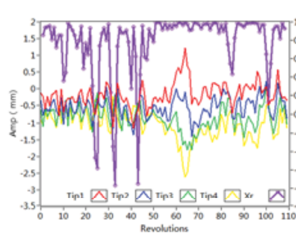


Figure 8. The comparison of the zero-drift curve

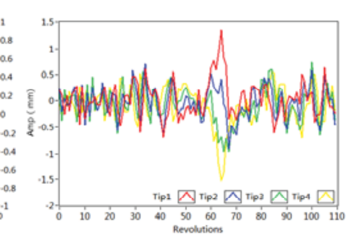
It is recommended to use more probes to calculate the correlation. The window width can be 2 or 3. When the number of probes is limited by the condition, the window width can be appropriately expanded.

IV. APPLICATION

In order to verify the effect of the correlation method to data zeroing, got the experimental data from blade rotor test bench[2]. Considering the experimental data points, the correlation curve is calculated with the window width is 2 and four probes signals to remove the zero drift. The calculation results of correlation and vibration displacement after data zeroing are shown in Fig.9. After data zeroing, the center line of the blade vibration displacement diagram returns to the zero reference line, which means zero drift has been eliminated.



(1).Correlation



(2).Blade displacement

Figure 9. Correlation results and data zeroing

Calculating the peak-to-peak changes of the experimental signal before and after zero drift. The results are shown in Table. II .

TABLE II. THE COMPARISON OF RELATIVE ERROR RELATED TO THE PEAK-TO-PEAK VALUE

Parameter		Tip1	Tip2	Tip3	Tip4
Peak-to-peak value(mm)	***Experimental data***	1.6846	1.3975	1.1521	1.5812
	Correlation method	1.6886	1.4250	1.1650	1.5763
Relative error	***Correlation method***	0.237%	1.968%	1.120%	0.310%

It can be seen from Table. II that the relative error of the peak-to-peak value of the correlation method is less than 2%, indicating that this method is effective. Due to the limited experimental conditions, the advantage of the correlation method will be more obvious at high-speed.

V. CONCLUSIONS

Data zeroing based on correlation and linear interpolation of the blade tip-timing data which firstly uses the form of the sliding window to calculate correlation is effective which can be applied to the preprocessing of blade vibration data. When using this method. choose the sliding window width of 2~4. Meanwhile, This method can identify the synchronous vibration in BTT data. The correlation method cannot distinguish the asynchronous response, the new method remains to be studied.

REFERENCES

[1] I. B. Carrington, "Development of blade tip timing data analysis techniques," University of Manchester, 2002.

[2] Xinqi Yu, "Investigation on High-Speed Rotating Blade Vibration Monitoring Method," Nanjing University of Aeronautics and Astronautics, 2019.

[3] P. Russhard, "Blade tip timing (BTT) uncertainties," AIP Conference Proceedings. vol. 1740, no. 1, 2016.

[4] Jian Huang, " Noise Processing Techniques for Vibration Signals of Rotating Blade," Tianjin University, 2016.

[5] Junhu Li, "Investigation on Vibration Parameters Identification Method of Rotating Blade Vibration," Nanjing University of Aeronautics and Astronautics, 2014.

[6] G. Dimitriadis, I. B. Carrington, and J. R. Wright, "Blade-tip timing measurement of synchronous vibrations of rotating bladed assemblies," Mechanical Systems and Signal Processing, vol. 16, no. 4, pp. 599-622, 2002.

[7] O. Jousselin, "Development of Blade Tip Timing Techniques in Turbo Machinery," The University of Manchester (United Kingdom), 2013.

[8] G. Schlagwein, and U. Schaber. "Non-contact blade vibration measurement analysis using a multi-degree-of-freedom model". Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 220, no.6, pp. 611-618, 2006.

[9] S. Heath, and M. Imregun. "A review of analysis techniques for blade tip-timing measurements." ASME 1997 International Gas Turbine and Aeroengine Congress and Exhibition. American Society of Mechanical Engineers, 1997.