A novel microwave-based dynamic measurement method for blade tip clearance through nonlinear I/Q imbalance correction

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Abstract: Blade is the core component of an aero-engine, and its blade tip clearance (BTC) directly affects engine efficiency and safety. Aiming to dynamically extract the BTC from the I/Q signal, a novel microwave-based dynamic measurement system through nonlinear I/Q imbalance correction is proposed. To accurately correct for non-linear amplitude attenuation, the proposed algorithm employs periodic segmentation, mapping amplitude decay effects to parameter distributions. To effectively localize the extraction BTC region, the Amplitude-phase Half Wave Extraction (APH) is proposed, which utilizes squared I/Q amplitude information to determine the BTC position and extract clearance information. Compared to existing methods, the proposed algorithm excels in signal correction under non-linear amplitude attenuation and achieves high-accurate BTC extraction. Experimental studies show an absolute mean error below 2 μm, a maximum mean error below 5 μm, and a repeatability mean error of 0.154 μm for a BTC variation of 0.17 mm.

Keywords: Microwave sensor, Blade tip clearance, I/Q Imbalance, Segmented Ellipse correction.

1.Introduction

Blade tip clearance (BTC) measurement plays a pivotal role in the optimal functioning of rotary blades, particularly in large rotating machines like aircraft engines, gas turbines, and steam turbines [1]. This measurement directly affects engine efficiency, thrust, and overall lifespan of the engine system [2]. Continuous monitoring and control of BTC are essential for enhancing engine efficiency and equipment safety. In recent years, the BTC measurement system based on the microwave phase difference ranging method has the advantages of wider bandwidth, compact sensor size and strong anti-pollution ability, which has attracted extensive attention from scholars. In the near-field measurements, the static I/Q signal exhibits a more pronounced amplitude modulation effect, resulting in the I/Q trajectory taking on a spiral shrinking shape [3] a characteristic that will directly lead to the failure of the correction method using the I/Q signal as a standard sine signal.

Aiming to extract the BTC from the I/Q signal effectively and accurately, a novel microwave-based dynamic measurement system through nonlinear I/Q imbalance correction is proposed. The segmented ellipse correction and kernel density estimation (S-EKD) is proposed to address the issue of ellipse correction failure caused by nonlinear fading problems. The ellipse correction signal length is determined by identifying peaks in the spectrum of preprocessed I/Q signals. Multiple sets of correction parameters are then solved using translational shifting with a certain step size, with the density average serving as the correction parameter. On the other hand, for dynamic tip clearance extraction, the Amplitude-Phase Half Wave Extraction (APH) method mainly utilizes the squared amplitude information of the I/Q signals to locate the demodulated BTC information. Subsequently, it identifies the BTC region based on the abrupt change in phase information between the blade and the blade sidewalls, ultimately facilitating the BTC measurement.

In summary, the main contributions of this work are listed as:

-It is one of the first attempts at an I/Q imbalance correction algorithm with amplitude nonlinear attenuation.

-Take advantage of unique features of the inter-organizational relationship between I/Q signal amplitude and phase, and the signal characteristics of the BTC region are fully considered to realize the BTC extraction.

-Full complete experimental procedure, dynamic experiments with multiple initial positions and multiple speed conditions.

2.Research content

A 120 GHz microwave sensor based on phase difference method is developed for blade tip clearance (BTC) measurement, as illustrated in Fig. 1.

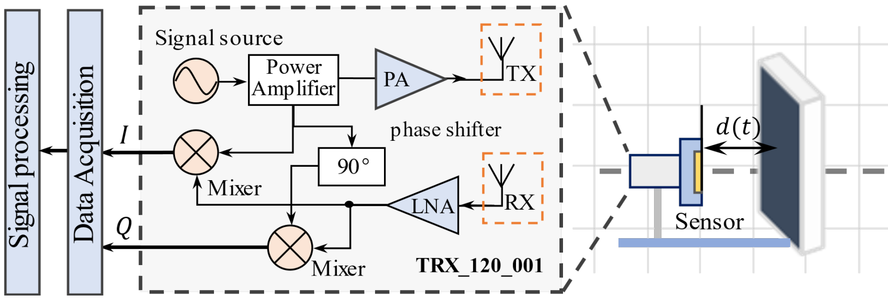

Fig. 1. The block diagram and measurement principle of CW Doppler radar.

The transmitted and received signals can be expressed as:

$$T_x = A_1 \sin(wt + \varphi_0)\ R_x = A_2 \sin(wt + \varphi_r)\ \#(1)$$

where A_1 and A_2 denote the energy of the transmitter and receiver signals φ_0 , represent the initial phase of the transmitter, while φ_r is the phase of the receiver.

The echo signal is down-converted by a mixer to produce a quadrature output baseband I/Q signal. I/Q signals exhibit nonlinear amplitude decay in near-field measurements, accompanied by amplitude-phase imbalance and DC offset, the baseband signals and can be expressed by the following equations:

$$\boldsymbol{I}(t) = \left[e^{-k\varphi_r(t)^2} + C\right] A\cos(2\pi f\varphi_r + \phi) + D_I\#(2)$$

$$\boldsymbol{Q}(t) = \left[e^{-k\varphi_r(t)^2} + C\right] \sin[2\pi f(\varphi_r + \Delta\phi) + \phi] + D_Q\#(3)$$

According to elliptical correction, the ratio of long diameter to short diameter , rotation angle , and the correction process of amplitude phase imbalance can be written as:

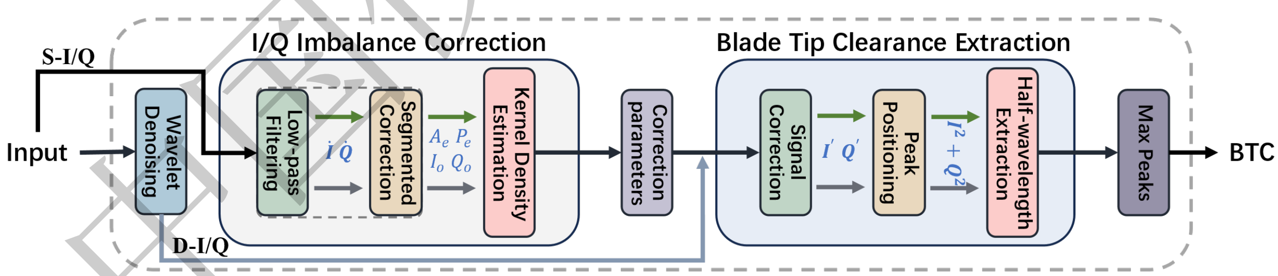

Fig. 2. The framework overview of the BTC extraction method: I/Q imbalance correction focuses on imbalance parameter solving by using S-EKD method; Dynamic BTC Extraction based on imbalance parameter and APH method.

Subsequently, dynamic BTC measurement can be accomplished through two stages: I/Q imbalance correction and dynamic BTC extraction as shown in Fig. 2. The I/Q imbalance correction stage focuses on obtaining the I/Q imbalance parameters, while the second stage utilizes these correction parameters to correct the dynamic I/Q data. Subsequently, demodulation is performed, and the BTC is extracted.

The S-EKD method can be divided into the following 3 steps:

Step 1: High-frequency interferences in the I/Q signals are eliminated by low-pass filtering, and concurrently calculating the peak frequency of each channel.

Step 2: The segmentation length is determined based on the peak frequency , and the segmentation matrix and are constructed with a fixed step size:

$$H_I = \begin{bmatrix} I_{1+0} & I_{2+0} & \cdots & I_{p+0} \\ I_{1+l} & I_{2+l} & \cdots & I_{p+l} \\ \vdots & \vdots & \ddots & \vdots \\ I_{1+ml} & I_{2+ml} & \cdots & I_{p+ml} \end{bmatrix} \#(5)$$

Then, the ellipse centers are fitted to each row of the I/Q matrix to estimate the ellipse parameters, thus obtaining sets of imbalance parameters $\boldsymbol{I}_o, \boldsymbol{Q}_o, \boldsymbol{A}_e, \boldsymbol{P}_e$.

Step 3: Utilizing kernel density estimation to estimate ellipse parameters distribution $\hat{f}_h(x)$ and obtain the median density corresponding to the elliptic parameter based on its probability distribution density.

After correcting the I/Q signal, the expansion is conducted to obtain the extended-range displacement change, calculated as follows:

$$d = \frac{\lambda}{4\pi}\{\text{unwrap}[\tan^{-1}(\boldsymbol{Q}'/\boldsymbol{I}')]\} \#(6)$$

where, $\text{unwrap}[\cdot]$ is the operation of phase unwrapping, is the operation of arctangent. Hence, following the aforementioned process, we employ the median of the parameter distribution as the correction parameter. Then, the APH method mainly utilizes the I/Q amplitude information $\boldsymbol{I}'^2 + \boldsymbol{Q}'^2$ of to locate the demodulated BTC position, and then determines the BTC region based on the mutation between the blade tip and the leaf base.

In BTC measurements at multiple locations, the same correction parameters are used and compare the two-period BTC information with the laser measurements separately. The absolute mean error, root mean square error, maximum error (μm), and microwave correction parameters with the laser measurements, are summarized in Table I.

Table I Calibration parameters and measurement errors

Calibration parameters							
1.496 2.077 0.775				0.596			
IP (mm)	RMS	Abs	Max	IP (mm)	RMS	Abs	Max
4.0	2.67	2.01	5.50	6.5	1.55	1.35	2.83
4.1	3.08	2.89	4.69	6.6	1.75	1.36	4.10
4.2	2.51	2.18	4.60	6.7	1.84	1.43	5.08

3.Conclusion

In conclusion, a novel dynamic BTC measurement approach utilizing a single 120 GHz microwave sensor is introduced in this paper. S-EKD and APH methods are proposed for I/Q signal imbalance correction and BTC extraction. The failure of ellipse correction is addressed by the proposed S-EKD, where the signal length is determined from the peaks of the I/Q signal spectrum, and the distribution density average of correction parameters is obtained. For static BTC measurement, an absolute mean error is 5.2 μm and a nonlinearity of 0.29% is achieved over a measurement range of 2.5 mm using the proposed method. For dynamic BTC measurement, an absolute mean error of 1.87 μm is achieved within 170 μm BTC variations, and the repeatability error is 0.154 μm. Future studies should more carefully consider the potential impact of complex shape blades on BTC measurements, and further improvement of static and dynamic correction and measurement accuracy is warranted.

References

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