IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 22, 2020, accepted March 9, 2020, date of publication March 16, 2020, date of current version April 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2980324

Research on the Tip Clearance Measuring Method Based on AC Discharge

BING YU, TAO ZHANG, HONGWEI KE, AND TIANHONG ZHANG
Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Corresponding author: Bing Yu (yb203@nuaa.edu.cn)

This work was supported in part by the Natural Science Foundation of China under Grant 51406083, and in part by the Fundamental Research Funds for the Central Universities under Grant NS2018017.

ABSTRACT A new measuring system for the engine tip clearance based on alternate current discharge is proposed in this article. Firstly, theoretical analysis and numerical simulation of the system, as well as the experiment of gas discharge are introduced to prove the feasibility of the method. Then a validation platform is built to study the effects of different probe materials and structures, as well as changes in temperature and humidity under atmospheric pressure on the system. Finally, the system calibration and tip clearance measurement are carried out. The results show that tungsten copper probe with planar structure is more suitable for measuring the tip clearance. When the tip clearance is between 0-6mm, the designed system has high measurement accuracy and its measurement error within 0.05mm. Compared with the traditional spark discharge method, the proposed method not only has the similar advantages, but also overcomes many defects, and has a broader application prospect.

INDEX TERMS Tip clearance, AC discharge, measurement accuracy, spark discharge method.

I. INTRODUCTION

Rrecently,the new aircraft has put forward higher performance and stability requirements for the engines, which has brought great challenges to the development of new engines. The tip clearance is the radial distance between the rotor blade tip and casing, which is an important parameter affecting the efficiency, stability and safety of engines. Meanwhile, how to optimize it is a key technology for improving the performance of an engine [1]. As the research work reported by the British RR company, the length of the gas turbine engine blade tip clearance increases by 1%, the efficiency of engine is reduced about 1.5%,while the fuel consumption rate increases about 3% [2].

The decrease of tip clearance can reduce the working medium leakage and the loss of the end wall, thereby to improve the engine performance. However, if the tip clearance is too small, with the effects of the factors such as blade load change, casing deformation and thermal expansion, the friction collision between blade and casing may occur, which will affect flight safety [3], [4]. Due to the engine is working in the environments of high temperature, high pressure and large vibration, there are many factors affecting the tip clearance during the actual working process. Thus tip clearance can't be accurately estimated by the theoretical simulation, its change situation only can be obtained by real-time measurement, thereby to optimize the design of the engine. Meanwhile, real-time detection and analysis of the tip clearance can not only verify the design parameters of the engine, but also predict the fault and reduce unnecessary economic losses.

At present, the traditional tip clearance measuring method based on gas discharge is mainly the discharge probe method, which is also called spark discharge method [5]–[7]. Discharge probe method is the tip clearance measuring method based on spark discharge principle. Its specific working process can be shown as follows. Firstly, the probe with DC (direct current) voltage is moved radially by a stepper motor, and then when gas discharge happens between blade tip and probe, the probe stops moving, and the tip clearance could be obtained by the moving distance of the probe from casing [8]. Davidson firstly designed the discharge probe sensor to measure the distance between the blade and the drum in 1983, and the method was applied successfully for the minimum tip clearance measurement in the following years [9]. The second-generation tip clearance measuring system based on discharge probe method was designed by Sheard in 1992, the system resolution is 2.5μm under the

The associate editor coordinating the review of this manuscript and approving it for publication was Christopher H. T. Lee.

measurement range of 6mm [8]. The discharge probe method was deeply researched by Watanabe after 1994, the system designed by him has a measurement accuracy of ±0.05mm [5], [6], [10], [11], however, the high realization costs and complex mobile devices made the system applications still be limited to experimental tests.

As a mature gap measurement method, spark discharge method has a relatively simple principle, and it can work at high temperature and pressure environment. However, the structure of the mechanical actuator applied to drive the probe is complex and the operation of the device must be skilled, which greatly limits its development [12]. With the development of technology, there are many other tip clearance measuring methods appeared including eddy current, capacitive, microwave and optical fiber methods [13]–[16]. Eddy current system has the advantages of the small size and weight, high precision. But this method can only measure the metal materials and the blade tip is required to have a certain thickness, meanwhile the poor heat resistance of eddy current sensor is the key problem to be solved to promote its practical application [13], [17]–[19]. Due to simplicity, low-cost and robustness of the capacitive system, the method has been used widely for measuring tip clearance. However, low spatial resolution, small measurement range, and need for calibration are the main defects which limit its applacation [14], [20]–[23]. Microwave method can be applied in the harsh environment to achieve non-contact measurement, and the system installation will not damage the casing. However, due to the wave nature of the microwaves, the wavelength has to be scaled down with the blade thickness which increases the difficulty of measurement [15], [24]–[26]. Optical fiber method has the advantages of simple structure, stable performance, strong resistance to electromagnetic interference ability, high sensitivity and resolution, but it also has some disadvantages. Among them, the blade reflection loss and high realization costs are the major problems to be solved [16], [27]–[30].

In order to enhance the application of tip clearance measuring methods and optimize the engine design, a novel measurement method based on AC discharge is proposed in the article. In Section 2, the proposed measuring system and theoretical analysis of its working principle are illustrated. Section 3 introduces the numerical simulation process of the system. The experiment of gas discharge, the effects of different probe materials and structures, as well as changes in temperature and humidity on the system are studied in Section 4. And in Section 5, the tip clearance measurement and analysis are performed. Finally, Section 6 draws the conclusions of this article and makes an outlook for the future work.

II. DESIGN OF THE TIP CLEARANCE MEASURING SYSTEM

A. THEORETICAL ANALYSIS OF THE SYSTEM WORKING PRINCIPLE

The particle moving diagram of gas discharge region is presented in Fig. 1, L is the distance between two electrodes. When the voltage between the two discharge electrodes

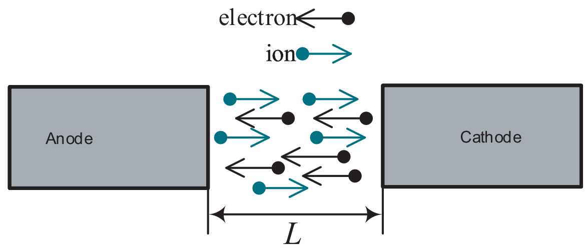


FIGURE 1. The particle moving diagram of gas discharge region.

increases, due to the positive and negative particles collided during their moving process, more charged particles are generated, thereby to increase the current. When the output voltage reaches the critical point, the discharge mode would be suddenly transferred from a Townsend discharge to a self-sustaining discharge, the phenomenon is called the breakdown of gas, this momentary voltage is called the ignition voltage or the breakdown voltage [31]. According to Townsend discharge theory [32], the breakdown condition can be expressed by Equation (1):

$$\gamma(e^{\alpha L} - 1) = 1 \tag{1}$$

where α is the first Townsend ionization coefficient, L is the discharge gap, γ is the third Townsend ionization coefficient, which is related with the electrode material.

According to Townsend discharge theory [32], α satisfies Equation (2):

$$\frac{\alpha}{P} = A\ exp(-\frac{B}{E/P}) \tag{2}$$

where P is the gas pressure, A , B are the constant relevant to the gas property, E is the electric field in the discharge region, $E = V_S/L$ and V_S is the output voltage of the power supply.

According to Equation (1) and (2), the following Equation can be obtained:

$$\ln(\frac{1}{\gamma} + 1) = APLe^{-BPL/V_s} \tag{3}$$

Solving the Equation (3):

$$V_S = \frac{BPL}{\ln(APL/\ln(1 + 1/\gamma))} \tag{4}$$

Equation (4) is called Paschen's law [32], when the gas type, gas pressure and electrode material are determined. A , B and γ become constants. According to Equation (4), it can be found that the gas breakdown voltage is only related to the electrode gap L under the normal temperature and atmospheric pressure. Therefore, the change of electrode gap would result in the breakdown voltage change, which can be used as the measurement principle of the designed system.

B. EXPERIMENTAL DEVICE

The structure diagram of the tip clearance measuring system based on AC discharge as shown in Fig. 2. The system is mainly composed of power module, metal probe, blade model, voltage measurement module, data processing

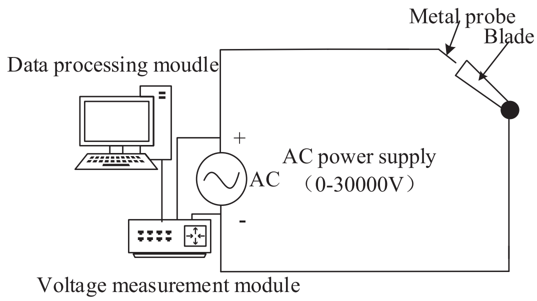


FIGURE 2. **The structure diagram of the tip clearance measuring system based on AC discharge.**

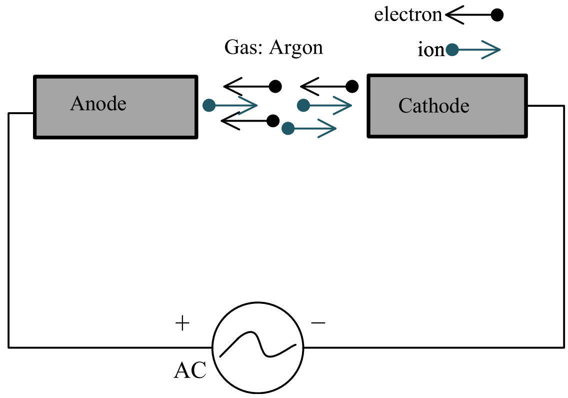


FIGURE 3. **The circuit model of the system.**

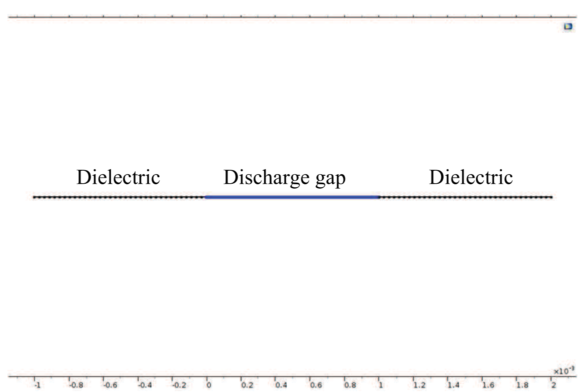


FIGURE 4. **Geometric structure diagram of two electrodes.**

module. The power module adopts an AC voltage source, the power supply device is CTP-2000K, and the output voltage of the power supply can be adjusted continuously between 0-30kV, and discharge frequency adjustable range is between 5-20kHz. The metal probe is made with metal material with good conductivity and heat resistance, its length is about 5cm and the diameter is about 1mm. The metal probe connected with high voltage terminal of the power supply device is as the anode, and the blade model connected with low voltage terminal of the power supply device is as the cathode. The gas discharge can happen between the probe and blade tip when the applied voltage reaches breakdown voltage. The discharge distance can be adjusted continuously between 0-6mm by displacement platform which model is LGX60-C, and its displacement accuracy is 0.01mm. The voltage measurement module is applied for measuring breakdown voltage. As a measuring part, the specific operation of the voltage measurement module can be described as follows. When the air discharge is happened, the circuit is on and there is an electrical signal. According to this mutation phenomenon, the voltage measurement module can record the voltage at this moment and take it as breakdown voltage. All the data acquired from the experiments are analysed and processed by the data processing module.

III. NUMERICAL SIMULATION

COMSOL Multiphysics is a large advanced numerical simulation software, it can analyze and compute multiple coupled physical fields and couplings solve the completely different logical domain and model [33], with its advantages, the software is employed to make numerical simulation of the system in the article. As shown in Fig. 2, a one-dimensional model of gas AC discharge has been established, as the composition of the air is very complex, up to now, numerical simulation in air still can not be realized. Due to argon is a single gas and the model of gas discharge is easy to realize in argon, this gas is selected as discharge gas in the model, the circuit model of the system is shown in Fig. 3. As the model with only two electrodes is hard to converge under standard atmospheric environment, in order to improve the convergence of the model, the insulating medium is added to two electrode surfaces. And then the breakdown voltage of different clearance can be obtained by numerical simulation.

The simulation environment of COMSOL Multiphysics makes the implementation of each step of the modeling and analysis process very convenient. The process of modeling using the software mainly includes the following steps:

1) Establishing corresponding geometric model.
   In order to simplify the computational complexity and improve the convergence of the model, a one-dimensional model of gas AC discharge is established and the geometric structure of two electrodes is presented in Fig. 4.
2) Defining physical parameters.
   Defining the physical parameters of the model means that the corresponding variables are simply set up in the preprocessing module, these parameters can either be constants or model variables, or can be functions based on time and location. The parameters are set up as follows, voltage amplitude and electrode gap L are adjustable.
3) Partitioning mesh.
   The software contains some units that partition the mesh, such as free triangles, free quads and rectangles. If more accurate results are required, mesh can be partitioned by users. In this article, a one-dimensional model of gas AC discharge is established. There are 200 elements across the width of the gap in order to make sure

TABLE 1. Model parameter setting.

Name	Expression	Description
freq	12e3[Hz]	Frequency
omega	2·pi·freq	Angular frequency
Vrf	821[V]·sin(omega·t)	Applied voltage
d	0.001[m]	Plate diameter
As	0.25·pi· d^2	Plate area
L	0.001[m]	Electrode gap
P	1[atm]	Gas pressure

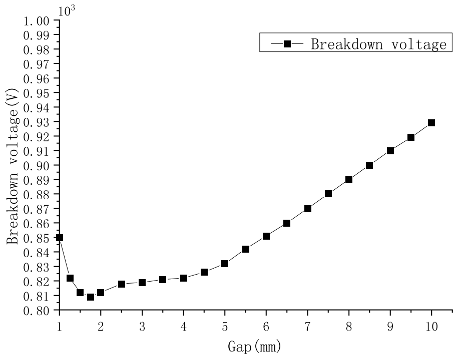


FIGURE 5. Relationship curve between the breakdown voltage and the electrode gap.

that there is sufficient mesh density to resolve the sharp gradients in the electron and ion density in the gap.

4) Loading and solving.
According to the micro-discharge characteristics of gas, when the electron density reaches $10^{14}m^{-3}$, the gas discharge could be considered to happen between electrodes [31], [34]. The electron density is just reaching $10^{14}m^{-3}$, which is the basis for judging the gas discharge in this article, and then the gas breakdown voltage at different gaps can be obtained. The electrode gap is adjusted within 1-10mm, and finally the obtained relationship curve is shown in Fig. 5.

As shown in Fig. 5, relationship curve between the breakdown voltage and the electrode gap satisfies Paschen curve [32], which proves the correction of the simulation. The breakdown voltage shows an increasing trend with the increase of the electrode gap between 1.75-10mm, which is consistent with the research results of the reference [35], [36], and verifies the correctness of the theoretical analysis and the feasibility of the proposed measurement method.

IV. EXPERIMENTAL RESEARCHES

A. THE EXPERIMENT OF GAS DISCHARGE

Before building the tip clearance measuring system, a simple gas discharge test platform is designed. Through obtaining the breakdown voltage at different electrode gaps to verify the correctness of the theoretical analysis and lay the foundation for designing the tip clearance measuring system.

High-voltage power supply CTP-2000K is applied to output continuously adjustable voltage. And the frequency is set to 12Khz. Two similar probes made with copper material are selected to carry out the experiment, their length is 5cm and

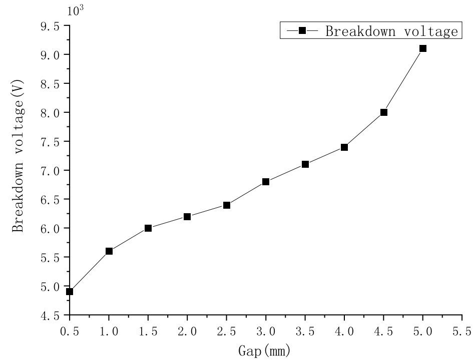


FIGURE 6. The relationship curve between the breakdown voltage and the gap under two copper probes.

the diameter is about 1mm. The gap between two probes can be adjusted within 0-5mm by displacement platform. Limited by experimental conditions which can't be supposed to adjust such a wide range of temperature and pressure as the real engine suffers, so what discusses in this paper is just the general conclusions under normal temperature and pressure. The relationship curve between the breakdown voltage and the gap is presented in Fig. 6.

As presented in Fig. 6, when the electrode gap is between 0.5-5mm, the breakdown voltage gradually increases with the increase of the electrode gap. Because the discharge gas used in the experiments is air, which is harder to be punctured than argon used in the simulation, the breakdown voltage is much bigger than the simulation results shown in Fig. 5. Also, for the operational safety of aero engines, active blade tip clearance control technology requires to control air gap around 2.5mm. So the different between the experimental result and the simulation result under low tip clearance plays an unimportant role in this paper. And it is worth noting that the experimental result of gas discharge has a similar trend with the simulation result that with the tip clearance increases, the breakdown voltage increases too, which verifies the correctness of theoretical analysis and simulation, meanwhile proves the feasibility of the proposed tip clearance measuring method.

B. THE EFFECTS OF PROBE MATERIAL

According to Equation (4), when the temperature, gas pressure and gas type are determined, the breakdown voltage of the gas is directly related with the probe material. Therefore, the influence of different probe materials on breakdown voltage is studied, which plays an important role in optimizing the tip clearance measuring system.

In order to study the influence of different probe materials on the system, the probes made of different materials, including copper, tungsten and tungsten copper, are employed to carry out the researches, the structure diagram of three probes with different materials is shown in Fig. 7. The output voltage is adjustable and the frequency is 12Khz. The distance between the blade tip and the probe is adjustable continuously between 0-6mm, the experimental environment is standard

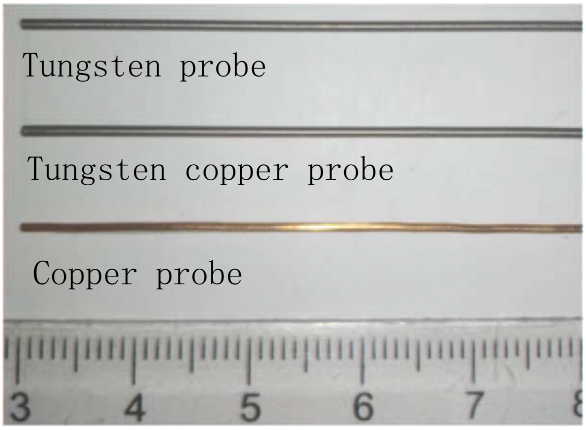


FIGURE 7. The structure diagram of three probe with different materials.

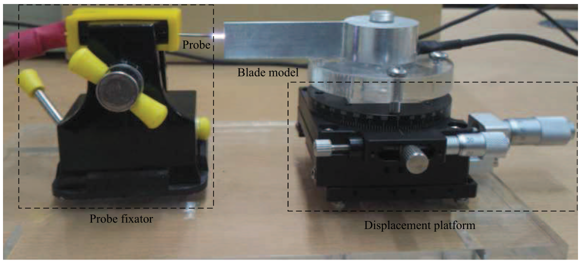


FIGURE 8. The experimental platform of the tip clearance measuring system.

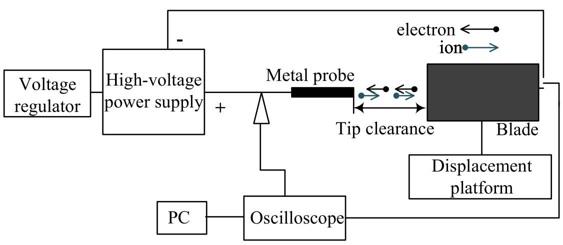


FIGURE 9. The work schematic diagram of the experimental platform.

atmospheric pressure air, the experimental platform of the tip clearance measuring system is shown in Fig. 8.

The work schematic diagram of the experimental platform is presented in Fig. 9. Firstly, the distance between the probe and the blade tip is fixed by the displacement platform, and then the output voltage gradually increases from zero by the regulator. When the output voltage increases to a certain value, the gas between the blade tip and the probe would break down and discharge happens, the breakdown voltage will be recorded by the voltage measurement module at the moment. Finally, the distance between the probe and the blade tip is varied continuously by the screw knob of the displacement platform, repeating the above process, the relationship curve between the breakdown voltage and the tip clearance could be obtained, the experimental result is shown in Fig. 10.

As shown in Fig. 10, the breakdown voltage raises with the increase of tip clearance. As the copper probe has good conductivity, its breakdown voltage is lower. However, the copper probe has a lower melting point, when gas discharge happens,

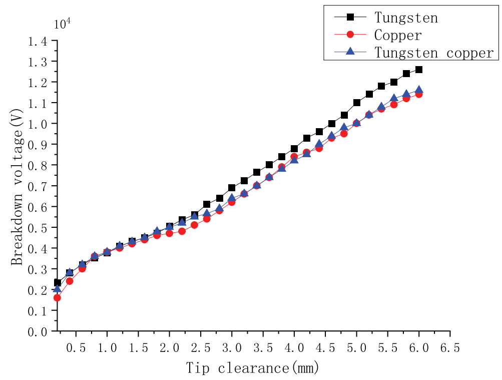


FIGURE 10. Relationship curve between the breakdown voltage and the tip clearance under different probe materials.

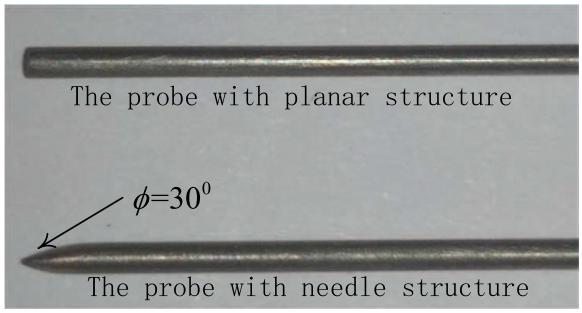


FIGURE 11. The structure diagram of the tungsten copper probe with different structures.

a large amount of heat is produced due to the collision between particles, which leads to the melting of the probe tip, thereby to form the measurement error. The tungsten probe has high heat resistance and is suitable for measuring the tip clearance in high temperature components. However, its breakdown voltage is higher and the power consumption is greater. The tungsten copper probe has the advantages of high heat resistance and good conductivity, therefore it is more suitable for measuring tip clearance.

C. THE EFFECTS OF PROBE STRUCTURE

In order to study the influence of different probe structures on breakdown voltage, tungsten copper probes with two different structures of plane and needle are introduced to carry out the experimental studies, the structure diagram of the tungsten copper probe with different structures is shown in Fig. 11. The output voltage is adjustable and the frequency is 12Khz. The distance between the tip and the probe is adjustable continuously between 0-6mm, the experimental environment is standard atmospheric pressure air, the experimental result is shown in Fig. 12.

As shown in Fig. 12, the tungsten copper probe with needle structure has lower breakdown voltage than the planar structure and is easier to discharge. This is because when the environment is unchanged, the sharper the tip, the greater curvature, and the power line is denser, which causes the potential gradient larger. Therefore, sharper place of the probe

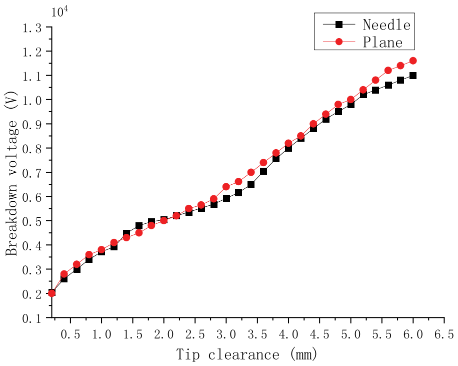


FIGURE 12. Relationship curve between the breakdown voltage and the tip clearance under different probe structures.

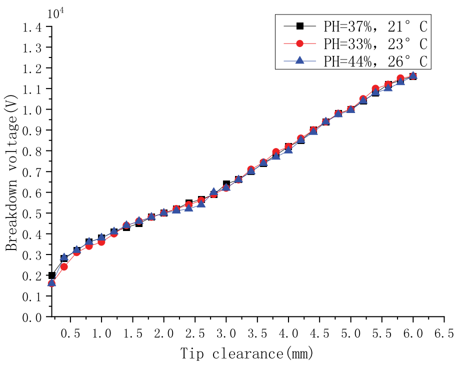


FIGURE 13. Relationship curve between the breakdown voltage and the tip clearance under three groups of temperature and humidity.

surface has greater charge density and its near electric field is stronger, the collision of particles is more intense under the action of electric field, which leads to the gas discharge occurs more easily, thereby to reduce the breakdown voltage effectively [37]. Although the breakdown voltage of the needle structure is lower, the breakdown voltage fluctuates greatly due to the extremely uneven electric field formed between the probe tip and blade, therefore, it is not suitable for the tip clearance measurement.

D. THE EFFECTS OF TEMPERATURE AND HUMIDITY

During the experimental researches, the humidity and temperature both change slightly at any time. It is very important to study the influence of changes in humidity and temperature on the measurement result under normal temperature and atmospheric pressure environment. The relationship between the breakdown voltage and the tip clearance under three different groups of temperature and humidity is recorded, the experimental result is shown in Fig. 13. Limited by the experimental conditions, the range of temperature and humidity is small, but it does not mean that the results are useless. In other words, these results verified a certain degree of stability of this measurement method.

As presented in Fig. 13, the influence of changes in temperature and humidity on the breakdown voltage does not change the shape of curves a lot and the difference of the breakdown voltage is within 200V, which is the acceptable range we defined under normal temperature and atmospheric pressure environment, therefore, the effects of their changes on breakdown voltage can be neglected basically. Although the water molecules in the air are strongly electronegative, which can capture free electrons to form ions, thereby to affect the breakdown voltage. However, because the velocity of the electrons in a uniform electric field and a slightly uneven electrical field is greatly fast under the action of strong electric field, which causes water molecules is difficult to capture electrons in high-speed motion, its inhibition to discharge is not obvious, therefore, the effect of small range of humidity can be neglected [38], [39]. The temperature under atmospheric environment is higher, the faster motion of molecules in the air, and then to affect the breakdown voltage. However, the experimental environment is under normal temperature and atmospheric pressure environment, the range of temperature variation is small, therefore, its effect on the breakdown voltage is also not obvious.

V. MEASUREMENT AND ERROR ANALYSIS

From the above experimental researches, it can be found that tungsten copper probe has higher melting point and lower breakdown voltage, which is more suitable for tip clearance measurement in high temperature environment. The probe with needle structure has a lower breakdown voltage, however, due to the extremely uneven electric field formed between blade and probe, breakdown voltage fluctuations greatly, so the probe with planar structure is more suitable. The effect of changes in temperature and humidity under normal temperature and atmospheric pressure is not obvious on the breakdown voltage, therefore, their influences can be neglected in the acceptable range.

In order to verify the practicability of the proposed measurement system. Firstly, the relationship between the tip clearance and the breakdown voltage needs to be calibrated, and then the measurement of the tip clearance and the error analysis are required to be carried out. A tungsten copper probe with planar structure is selected in the article, its diameter is 1mm and the length is 5cm. The output voltage is adjustable and the frequency is 12Khz. The distance between the tip and the probe is adjustable continuously between 0-6mm, the experimental environment is standard atmospheric pressure air, the relationship curve is calibrated as Fig. 14.

As shown in Fig. 14, as the tip clearance increases, the breakdown voltage shows an increasing trend, and there is a better linear increasing relationship between them. After the relationship between the breakdown voltage and the tip clearance is calibrated, the measurement of tip clearance and the error analysis are also necessary. Firstly, the distance between the blade tip and the discharge probe is changed by the displacement platform, then the output voltage is continuously increased from zero, and the breakdown voltage at this distance is recorded. Finally, the tip clearance can be obtained by the calibrated relationship curve. However, there

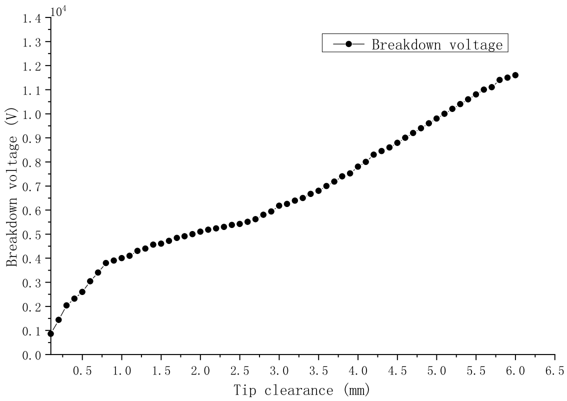


FIGURE 14. The calibration curve of the relationship between the breakdown voltage and the tip clearance.

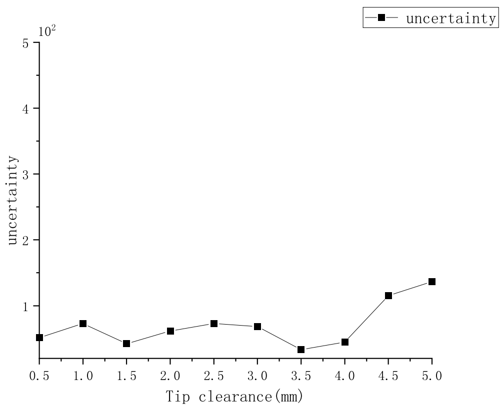


FIGURE 15. The uncertainty of the experimental device.

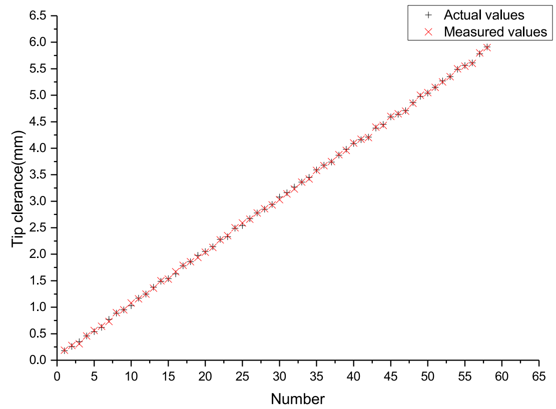


FIGURE 16. The scatter diagram of actual and measured values.

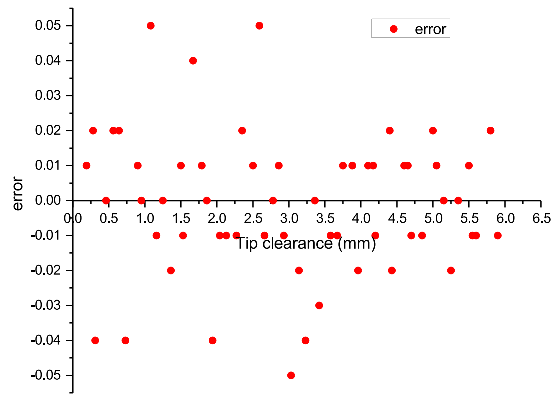


FIGURE 17. The diagram of the error distribution.

is an unavoidable error between the measured tip clearance and the actual distance, in order to verify the applicability and practicability of the measurement system, it is extremely important to analyze the error between the measured and actual values.

In order to introduce the uncertainty of the experimental device clearly, the uncertainty of the experimental platform under different tip clearances are shown in Fig. 15. In this paper, Bessel formula method is used to get the experimental standard deviation $s(x_k)$. And the standard uncertainly can be gotten with the Equation(5).

Where n is the number of measurements, in this paper, n equals 6. And the degree of freedom is 5. From the picture, it is obvious that the range of the uncertainty is between. Though it may looks like a large range and the biggest uncertainty is 136.56, when compares it to the values of discharge voltage under same tip clearance, it only accounted for 1.5%. So a conclusion can be drawn that the measurement error of the experimental device is very small, and it can play a role in the measurement of the aero-engines tip clearance.

$$u_A(\bar{x}) = \frac{s(x_k)}{\sqrt{n}} \tag{5}$$

According to the breakdown voltage at an unknown tip clearance, the function TREND of excel is applied to obtain the tip clearance from the calibration curve. In order to explain specific ideas clearly, a brief introduction to the use of the TREND function is given. As shown above, with the experiment results, a series of points about the breakdown voltage and the tip clearance have been obtained. But the breakdown voltages which are outside the measuring points remain unknown, in order to get a continuous curve which can be named as the True-Reference calibration curve, the TREND function is used to connect two adjacent known points. By this way, a curve which is piecewise linearly connected can be obtained, and it becomes the True-Reference calibration curve. After that, when the breakdown voltage is known, the corresponding tip clearance can be known through the curve.

The distance between the blade tip and the discharge probe is changed randomly by the displacement platform, 58 groups of tip clearance are measured with random distances while the other factors keep the same, the scatter diagram of actual and measured values is shown in Fig. 16, the diagram of the error distribution is presented in Fig. 17.

As presented in Fig. 16, most measured values are not consistent with actual values, measurement error of the proposed measuring system is inevitable. And with the Fig. 17, we can find that the error of measurement results is within ±0.05mm, the error of most measured values is within ±0.02mm. So a conclusion can be drawn that there is a high agreement degree between measured and actual values, and the tip clearance measuring system designed preliminarily has better measurement accuracy, its practicability is high. Compared with the traditional spark discharge method, the proposed measuring method based on AC discharge not only effectively avoids the inconvenience of installation and operating difficulties which mechanical actuator brings, but also improves the safety of the measurement system and eliminates dangers of collision and friction generated by the probe movement. Therefore, with the deeper study of this method, it will play an important role in engine optimization design and safety control, meanwhile effectively improve the efficiency and stability of the engine.

VI. CONCLUSION AND FUTURE WORK

In the article, theoretical analysis and numerical simulation of the proposed tip clearance measuring system, as well as the experiments of gas discharge are introduced to prove the feasibility of the measuring method. And then the effects of different probe materials and structures, as well as changes in temperature and humidity under normal temperature and atmospheric pressure on the measuring system are studied. The experimental results show that the tungsten copper probe with planar structure is more suitable for measuring the tip clearance, the influence of temperature and humidity changes on breakdown voltage is not obvious under normal temperature and atmospheric pressure environment, when the tip clearance is between 0-6mm, the designed system has high measurement accuracy and the error between measured value and actual values is smaller than 0.05mm. Compared with the traditional spark discharge method, the proposed method not only has similar advantages, but also overcomes many defects of spark discharge method, and it will have a broader application prospect in the field of the engines.

For the purpose of enhancing the application of the proposed measuring system, we will focus on mechanical design optimization, and we will improve our experimental device so it can provide similar environment as the real engine suffers and explore related experiments. Eventually realize the tip clearance measurement of high temperature components with our measurement method.

REFERENCES

[1] X. H. Fan and M. C. Zhu, and S. L. Nie, "Image measuring system of engine tip clearance," *J. App. Opt.*, vol. 4, no. 33, pp. 743–746, 2012.

[2] L. Qiu and Z. Wang, "Research on the measurement of aeroengine tip clearance," *Aeroengine*, vol. 4, no. 4, pp. 26–29, 2014.

[3] S. Korson and A. J. Helmicki, "An H ∞ based controller for a gas turbine clearance control system," in *Proc. Int. Conf. Control Appl.*, Sep. 1995, pp. -154–1159.

[4] X. Zhou, H. Zhang, J. Wang, "Research on turbine tip clearance modeling considering active tip clearance control," *J. Propuls. Technol.*, vol. 36, no. 7, pp. 1093–1102, 2015.

[5] N. Zhang and C. F. Huang, "Measuring technology of blade tip clearance of aeroengine," *Aeronaut. Manuf. Technol.*, vol. 13, no. 7, pp. 41–45, 2010.

[6] T. Watanabe, "Study on tip clearance measurement system: 2^{nd} report, characteristics of the system and measurement," *Trans. Jpn. Soc. Mech. Eng. Ser. C*, vol. 63, no. 609, pp. 1510–1515, 1997.

[7] E. C. Warren, "Tip clearance probe including anti-rotation feature," U.S. Patent 13 600 299, Mar. 6, 2014.

[8] A. G. Sheard and S. R. Turner, "Electromechanical measurement of turbomachinery blade tip-to-casing running clearance," in *Proc. Int. Gas Turbine Aeroengine Congr. Expo.*, 1992, pp. 1–10.

[9] D. P. Davidson and R. D. DeRose, and A. J. Wennerstrom, "The measurement of turbomachinery stator-to-drum running clearances," in *Proc. Int. Gas Turbine Conf. Exhibit*, 1983, pp. 1–5.

[10] T. Watanabe, "Measurement of tip clearance of all blades and the maximum tip clearance using discharge-type tip clearance measurement system," *Trans. Jpn. Soc. Mech. Eng.*, vol. 67, no. 67, pp. 1478–1483, 2001.

[11] T. Watanabe and M. Matsuki, "Study of tip clearance measurement system," *Trans. Jpn. Soc. Mech. Eng. C*, vol. 60, no. 67, pp. 2090–2095, 1994.

[12] C. Feng and B. I. Si-Ming, "Research of blade tip clearance measurement based on laser triangulation," *Turbine Technol.*, vol. 4, no. 53, pp. 267–270, 2011.

[13] K. S. Chana, M. T. Cardwell, and J. S. Sullivan, "The development of a hot section eddy current sensor for turbine tip clearance measurement," in *Proc. Turbo Expo, Turbine Tech. Conf. Expo.*, 2013, pp. 56–60.

[14] G. R. Sarma and J. P. Barranger, "Capacitance-type blade-tip clearance measurement system using a dual amplifier with ramp/DC inputs and integration," *IEEE Trans. Instrum. Meas.*, vol. 41, no. 5, pp. 674–678, Oct. 1992.

[15] T. Holst, T. Kurfess, S. Billington, J. Geisheimer, and J. Littles, "Development of an optical-electromagnetic model of a microwave blade tip sensor," in *Proc. AIAA/ASME/SAE/ASEE Joint Propuls. Conf. Exhibit*, 2013, p. 4377.

[16] H. Guo, F. Duan, G. Wu, and J. Zhang, "Blade tip clearance measurement of the turbine engines based on a multi-mode fiber coupled laser ranging system," *Rev. Sci. Instrum.*, vol. 85, no. 11, Nov. 2014, Art. no. 115105.

[17] W. Wang, W. Wang, H. Shao, L. Chen, and H. Song, "Investigation on the turbine blade tip clearance monitoring based on eddy current pulse-trigger method," in *Proc. Turbomach. Tech. Conf. Expo.*, 2016, pp. 583–587.

[18] C. Roeseler and A. P. von Flotow, and P. Tappert, "Monitoring blade passage in turbomachinery through the engine case (no holes)," in *Proc. IEEE Aerosp. Conf.*, Mar. 2002, p. 6.

[19] K. S. Chana and D. N. Cardwell, "The use of eddy current sensor based blade tip timing for FOD detection," in *Proc. Turbo Expo, Power Land, Sea, Air*, 2008, pp. 1–10.

[20] T. Fabian, S. Kang, and F. Prinz, "Capacitive blade tip clearance measurements for a micro gas turbine," in *Proc. 19th IEEE Instrum. Meas. Technol. Conf.*, May 2002, pp. 1011–1015.

[21] D. Müller, A. G. Sheard, S. Mozumdar, and E. Johann, "Capacitive measurement of compressor and turbine blade tip to casing running clearance," *J. Eng. Gas Turbines Power*, vol. 119, no. 4, pp. 877–884, Oct. 1997.

[22] T. Fabian, F. B. Prinz, and G. Brasseur, "Capacitive sensor for active tip clearance control in a palm-sized gas turbine generator," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 3, pp. 1133–1143, Jun. 2005.

[23] A. Steiner, "Techniques for blade tip clearance measurements with capacitive probes," *Meas. Sci. Technol.*, vol. 11, no. 7, pp. 865–869, Jul. 2000.

[24] R. Grzybowski, G. Foyt, H. Knoell, W. Atkinson, and J. Wenger, "Microwave blade tip clearance measurement system," in *Proc. ASME Int. Gas Turbine Aeroengine Congr. Exhib.*, 1996, pp. 1–6.

[25] A. Maslovskiy, "Microwave turbine tip clearance measuring system for gas turbine engines," in *Proc. ASME Turbo Expo, Power Land, Sea, Air*, 2008, pp. 105–114.

[26] M. Violetti, A. K. Skrivervik, Q. Xu, M. Hafner, "New microwave sensing system for blade tip clearance measurement in gas turbines," in *Proc. SENSORS*, Oct. 2012, pp. 1–4.

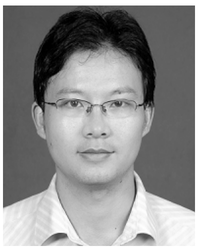
[27] I. Garcia, J. Zubia, A. Berganza, J. Beloki, J. Arrue, M. A. Illarramendi, J. Mateo, and C. Vazquez, "Different configurations of a reflective intensity-modulated optical sensor to avoid modal noise in tip-clearance measurements," *J. Lightw. Technol.*, vol. 33, no. 12, pp. 2663–2669, Jun. 15, 2015.

[28] H. S. Dhadwal and A. P. Kurkov, "Dual-laser probe measurement of blade-tip clearance," *J. Turbomachinery*, vol. 121, no. 3, pp. 481–485, Jul. 1999.

[29] I. García, J. Beloki, J. Zubia, G. Aldabaldetreku, M. Illarramendi, and F. Jiménez, "An optical fiber bundle sensor for tip clearance and tip timing measurements in a turbine rig," *Sensors*, vol. 13, no. 6, pp. 7385–7398, 2013.

[30] T. Pfister, L. Büttner, J. Czarske, H. Krain, and R. Schodl, "Turbo machine tip clearance and vibration measurements using a fibre optic laser Doppler position sensor," *Meas. Sci. Technol.*, vol. 17, no. 7, pp. 1693–1705, Jul. 2006.

[31] G. N. Wu, *High Voltage Technology*. Hobeken, NJ, USA: Machinery Industry Press, 2014.
[32] Z. C. Wu, X. J. Zhang, and Y. Z. Hu, *Gas Discharge*. Beijing, China: National Defence Industry Press, 2012.
[33] Z. Feng, Y. Xu, X. Li, K. Chang, Y. Dai, Q. Wang, and G. Hu, "Optimum electromagnetism design based on co-simulation of MATLAB and COMSOL," *Electromagn. Anal. Appl.*, vol. 1, no. 1, pp. 13–17, 2012.
[34] T. Ding, J. Liu, and A. Zhu, "Electrode configuration and plasma reactor of spark discharge," *Hejubian Yu Dengliziti Wuli/Nucl. Fusion Plasma Phys.*, vol. 34, no. 3, pp. 282–288, 2014.
[35] J. L. Walsh, Y. T. Zhang, F. Iza, and M. G. Kong, "Atmospheric-pressure gas breakdown from 2 to 100 MHz," *Appl. Phys. Lett.*, vol. 93, no. 22, Dec. 2008, Art. no. 221505.
[36] Y. T. Zhang, J. Lou, Q. Li, and Q. Li, "Electrode-gap effects on the electron density and electron temperature in atmospheric radio-frequency discharges," *IEEE Trans. Plasma Sci.*, vol. 41, no. 3, pp. 414–420, Mar. 2013.
[37] G. P. Diao, H. Zhang, and J. P. Jiang, "Ionic tube for air purification," CN Patent 102 522 702 A, Jun. 27, 2012.
[38] S. Mei, "Research on the influence of humidity on the breakdown voltage of air gap for electrical equipments," *Electr. Weld. Mach.*, vol. 9, no. 9, pp. 46–50, 2015.
[39] H. Niu, X. Zhuang, Z. Yi, Y. Liu, and G. Zhang, "Meteorological condition of dramatic decline of air gap breakdown voltage," *High Voltage Eng.*, vol. 40, no. 11, pp. 3343–3348, 2014.



BING YU received the B.S. degree in automation and the Ph.D. in degree in navigation guidance and control from Southeast University, China, in 2002 and 2009, respectively.

He is currently an Associate Professor and a Master Supervisor with Nanjing University of Aeronautics and Astronautics. His current research interests include the control and testing of the aircraft engine.

TAO ZHANG received the B.S. degree in instrument science and engineering from Southeast University, China, in 2018. He is currently pursuing the master's degree in power engineering with the Nanjing University of Aeronautics and Astronautics.

HONGWEI KE received the B.S. degree in flight vehicle propulsion engineering from the Nanjing University of Aeronautics and Astronautics, China, in 2017, where he is currently pursuing the master's degree in aerospace propulsion theory and engineering.

TIANHONG ZHANG received the Ph.D. degree from the Nanjing University of Aeronautics and Astronautics, in 2001. He is currently a Professor and a Ph.D. Supervisor with the Nanjing University of Aeronautics and Astronautics. His current research interests include aero-engine control, test, and measurement.