Optimized Research for Aero Engine Off-gas Monitor

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ABSTRACT: Since the majority of aero engine faults are aero engine gas path faults, it is important to monitor its working condition. But the monitoring is under the condition where electrostatic signal of charged particles in aero engine gas path is weak and the sensor works in an environment of high temperature and high noise, so that it is difficult to monitor continuously. Using the gas-solid two phase flow device to simulate the aero engine gas path, and designing a signal processing circuit and simulate the signal processing circuit in the software MULTI-SIM, and using the software LabVIEW to establish the virtual instrument data acquisition system, a monitoring model which include a data acquisition system and a aero engine gas path fault analyze system is designed. As a result, the model which can be adapted to high temperature and high noise, and is sensitive to charge signal, has the advantages of high resolution, high signal-to-noise ratio, and high stability, could be operated steadily and continuously in various working condition of aero engine, and could provide a reliable basis for fault diagnosis of aero engine gas path.

Keywords: aero engine; electrostatic sensor; charge amplifying circuit; data acquisition system of virtual instrument; fault analyze system

1 INTRODUCTION

Aero engine is an important integral part of the aircraft which is used for powering aircraft. Despite the rapid development of aero engine technology, the aero engine in a high-intensity work state for a long period, of which components damage easily, and in the harsh working environment may lead to short material life, non-normal lubrication and wear failure, etc. The statistics of American Air Transport Association in 1980-2001 showed that failures related to aero engine gas path components accounted for 21%. The engine is very important for flight safety, therefore, control failure rate, especially gas path component failure rate, is particular significant. Thus, the work condition of aero engine gas path must be monitored to provide effective protection for the safe operation of the aero engine.

In the current study, the electrostatic signal of the inhalable particles of aero engine, and the reason of aero engine gas path fault caused by the inhalable particles have been analyzed. And the electrostatic sensor and charge-sensitive amplifier circuit have been designed. The above mentioned researches provide a basic of electrostatic signal acquisition and aero engine gas path fault diagnosis, however, the method for continuous electrostatic signal acquisition in the harsh working environment and recognizing the aero engine gas path fault automatically is to be studied.

Due to the problem of the electrostatic signal is weak, the gas-solid two phase flow device which includes the composite electrostatic sensor is used, so that the data collected by sensors can complement each other, and can enable the monitoring of the weak electrostatic signal further optimized. Additionally, the virtual instrument acquisition system for the charge signal acquisition and processing is used because it is operated on a computer which avoids the actual instrument error, improves the acquisition precision, and is not limited to the poor working conditions and noise of aero engine gas path, which ensures the stability of monitoring. The solid-gas flow device is used to simulate aero engine operation, charged conditions of particles in fault condition and analysis the charged signal, to establish fault analysis system for recognizing the gas path fault characteristic signal and further improving the aero engine off-gas monitoring technology.
Emissions from aero engine gas path consist of two parts: 1) Soot produced by combustion of solid fuel, including carbon dioxide, nitrogen oxides, water vapor, hydrocarbons, carbon monoxide, sulfur oxides and incomplete combustion of carbon particles etc. 2) Particles generated from aero engine component wear, such as stress-induced material particles produced by wearing and generated from wearing between blades and casing or seal component etc. When the aero engine is in good condition, the particle size range is mainly in 5-7nm and 20-40nm. When the aero engine gas path component fails, it will produce abnormal particle which size is greater than 40nm. Because the particles moving in the gas path may generate static electricity, solid particles in different types and sizes moving in the gas path will produce various characteristics of the electrostatic signal. Gas path electrostatic signal monitoring can reflect the wear condition of aero engine gas path components. However, electrostatic signal in the gas path of aero engines is too small to collect, and due to poor working conditions and noise, it is difficult to carry out continuous monitoring. The present design is based on the principle of electrostatic induction, which uses the electrostatic sensors and signal processing circuit to collect the weak gas path electrostatic signal. After that, the virtual instrument acquisition system based on LabVIEW is used to acquire the electrostatic signal and display it, which could ensure the persistent and stability of the monitoring model.

Since the size of solid particles in aero engine gas path in normal operation is only nano scale with a very weak charge, of which magnitude is only \(10^{-19}\) C to \(10^{-17}\)C, and magnitude of wear particle size is only micron, which also with a very weak charge, of which magnitude is only \(10^{-17}\)C to \(10^{-15}\)C, such that the sensors in the gas path must very sensitive and the system require a good anti-jamming capability in order to accurately capture the charged signal. In operation, the system must have high stability, in order to continuously monitor the charge signals and identify the type of signal which may represent aero engine gas path fault.

Since the charge signal process is inconvenient, and the charge signal has very weak noise, thus the signal’s needed processes include Q/V transform, amplify, filtering, etc. The processed signal may be collected by the virtual instrument acquisition system and its feature could be displayed such that the signal which may represent aero engine gas path fault may be easy to be recognized. Suppose that \(q\) is a charge, in the center \(q\) with radius \(x\) to make a closed surface \(s\), according to Gauss theorem, the electric field intensity of \(s\) is:

\[
E = \frac{q}{\varepsilon \cdot 4\pi x^2}
\]

Wherein \(\varepsilon = \varepsilon_0 \varepsilon_r\) and \(\varepsilon\) is dielectric constant within surface \(s\), \(\varepsilon_0\) is dielectric constant in the vacuum, \(\varepsilon_r\) is dielectric constant in actual medium. Suppose that the amount of charge sensed by the sensor is \(Q\), sensing region of the sensor is \(A\), along the surface of the sensor to make a Gaussian surface, its electric flux can be approximated as:

\[
AE_A \propto \frac{Q}{E}
\]

wherein \(E_A\) is the electric field strength in region \(A\), \(\propto\) represents the relationship of direct ratio, \(E_A = E\), so that:

\[
Q \propto \frac{Aq}{x^2}
\]

that is, induced charge \(Q\) is proportional to the amount of charge \(q\), and is inversely proportional to the square of the distance between them.

Electrostatic sensor equivalent circuit is shown in Figure 1, wherein the amount of induced charge on the sensor probe is \(Q(t)\), output voltage is \(U(t)\), \(R\) is the equivalent resistance of the circuits, and \(C\) is the equivalent capacitance of circuits.

**Figure 1. Electrostatic sensor equivalent circuit.**

### 3 SIGNAL PROCESSING CIRCUIT

Herein, the signal processing circuit is divided into two parts: charge amplifier circuit and low-pass filter circuit. First, charge signal is converted into a voltage signal, and then the voltage signal is amplified, and finally performs low-pass filtering to the voltage signal.

Charge amplifier circuit with the following characteristics: (1) High sensitivity about charge (2) Value of the output voltage is proportional to the amount of charge. (3) Strong anti-jamming performance.

Therefore, a demand of selecting circuit components for the charge amplifier circuit is very high. For example, an inductor connected probe selected inappropriately would affect the sensitivity of charge amplifier circuit while producing greater noise, and coupling resistor inappropriately will produce zero drift. Thus, after the charge amplifier circuit, the charge
signal can be converted to a voltage signal proportionally which has a good testability and analytical.

3.1 Charge amplifier circuit

The charge amplifier circuit is shown in Figure 2 which in essence is the value of the high output impedance charge into a low output impedance voltage value, i.e., Q/V transform, amplifying a voltage value, wherein the value of the voltage is proportional to the charge value.

In the Q/V section, wherein C1 and C5 are capacitances with a noise filtering function, which need to use low-noise polystyrene capacitors, and the capacitance value should be as small as possible, in order to ensure a high charge sensitivity, such that the weak charge signals can be collected, herein the capacitor C1 = C5 = 1pF. R5 is the pull-up resistor between the input terminal and ground and ensures that the charge amplifier circuit can operate stably and reduce zero drift, which needs metal film resistors with high stability and high precision, and the resistance should be as large as possible so as to reduce noise, herein R5 = 500Ω.

In the amplifier section, single-ended differential mode amplifier is used to input signal to improve the signal - noise ratio, and suppress noise. Amplifier is divided into three stages, and the output end of Q/V transform section is connected with base electrodes of two transistors, i.e. Q1 and Q2, to input the voltage signal to the first stage amplifier. The second and third stages of amplifier are connected to capacitors to decrease noise, and a DC negative feedback is added in the second stage amplifier, in order to ensure stable magnification. Also, for the sake of ensuring good linearity and overcoming the zero drift, the direct coupling between the second and the third stage amplifier is used via resistance. To ensure the magnification, R11 and R12 should be over 50kΩ, while Rf1 and Rf2 need smaller resistance, herein Rf1 = Rf2 = 1kΩ. The charge amplifier circuit is shown in Figure 2.

3.2 Low-pass filter circuit

In addition to valuable information in the signal, a noise signal is further included. The noise is from the pipe vibration, air flow interference and electromagnetic interference when power is applied. Hence the voltage-controlled low-pass filter is selected to filter high frequency noise. The low-pass filter circuit is shown in Figure 3.

Similar to the charge amplifier circuit, the integrated amplifier of low-pass filter circuits are also added to the capacitors to reduce noise. Further, use direct coupling between the output terminal of the charge
amplifier and the low pass filter circuit input terminal by resistance to ensure good linearity and overcoming zero drift (See Figure 3).

Simulate the above circuit in MULTISIM software, and we can get the amplitude-frequency characteristic diagram as shown in Figure 4.

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Figure 4. Amplitude-frequency characteristic.

4 THE RESULTS

4.1 Measurement results using corn flour and silica powder as charged particles

The gas-solid two phase flow device mixes the solid particles and the gas in the pipeline and blows them to make them flow. The corresponding theory is widely used in industry (such as power station, and steel mill), military (such as ignition tube, and propulsion unit), and aviation industry (such as aero engine). Herein, the gas-solid two phase flow device is used to simulate the aero engine gas path. The gas-solid two phase flow device is shown in Figure 5. Gas is blown by the fan and flows in the pipeline, and corn flour, silica powder etc. are added in it, to simulate the motion of the aero engine gas path wear particles. Installing two electrostatic sensors in the pipeline, i.e. needle-shaped and ring-shaped electrostatic sensor, the sensor is equipped with the same signal processing circuit for the measured data to complement each other. In the rear end of the signal processing circuit, a virtual instrument acquisition systems based on LabVIEW is used, and signal processing circuit output is connected with NI capture card which can transfer data to a computer, which LabVIEW software can be used for data acquisition and process (See Figure 5).

The flowchart of the acquisition system is shown in Figure 6. In the LabVIEW software, NI-DAQmax function can be used to acquire the data transmitted by the NI capture card, the NI-DAQmax function may include creating a virtual channel function, trigger function, starting task function, timing function, reading function, writing function, waiting until end function, and cleaning function. To use the LabVIEW software to acquire data, the above functions should be used with a cyclical function and a waveform screen which is linked to the writing function to display the signal indicative of the data transmitted by the NI capture card (See Figure 6).

Figure 5. The gas-solid two phase flow device.

Figure 6. The flowchart of the acquisition system.
In the pipeline of Gas-solid two phase flow device, in order to simulate the situation of the aero engine off-gas, a little silica powder and corn flour is added, the solid particle in the pipeline is very thin, which is under 0.01%, thus the charge amount Q is very small. Corn flour particle size is relatively large and insulating, while silica powder particle size is smaller and is semiconductor particle. More silica powder and less corn flour are added into the pipeline, needle-shaped electrostatic sensors and ring-shaped electrostatic sensor, and signal acquisition results are shown in Figure 7 and 8, respectively.

![Figure 7. Acquisition result of the needle-shaped electrostatic sensors.](image)

As shown in Figure 7 and 8, when the silica powder is blown into the pipeline, because its size is smaller, and the particles intensive, the needle-shaped sensor acquired waveform is continuous, so the ring sensors can measure the signal trend. From the figure we can see the movement of silica powder in gas-solid two phase flow device, and the acquisition result of its effective charge signal is between 0 to 0.002mV. When corn flour is blown into the pipeline, due to its larger size, it could take more charges, resulting in a significant change in the signal. Corn flour particles in gas-solid two phase flow device moves, and the acquisition result of its effective chargesignal is between 0.01 to 0.025mV.

4.2 Aero engine gas path fault analysis system

As described above, the gas path components on which stress is exerted in high-temperature environment could produce particles by wear, also, wear between the blades, the casing, and the seal could produce particles. And particles are produced when aero engine gas path components wear is different from those signals in normal operation in their size range. The characteristic of signal of particles produced by wear and in normal operation is similar to the characteristic of signal of and silica powder which flowed in the pipeline of the gas-solid two phase flow device. The difference between the signal produced by wear and the signal in normal operation is very large, which is similar to the difference between the signal of corn flour and the signal of silica powder. When the aero engine is in normal operation, a continuous and weak signal can be acquired by acquisition system, and when the fault occurs, the abnormal particles would be presented, and the signal would gain by several times to hundreds of times, which is discontinuous. Therefore, when the gain of signal occurs and gained signal is discontinuous, we can infer that some faults may occur in the gas path of aero engine, and we should check the wear condition of the gas path components. The aero engine gas path fault analysis system can be established based on the method mentioned above.

When aero engine is in normal operation, the signal acquired in pipeline is continuous and weak, and when the fault occurs, the signal would gain by several times to hundreds of times, which is discontinuous. Thus a system based on LabVIEW is designed which is used for determining whether faults occurs in aero engine gas path. When the aero engine works, the amplitude of signal should be recorded in T1 (T1>0) which is used to compare with that of the signal which is detected in T2 (T2>T1). If the latter is from several times to hundreds of times (even more) compared to the former, the present of abnormal particles could be determined, and if the greater signal presents frequently (such as in T3,T4… and T3>T2 ,T4>T3…) and discontinuous, we can determine that the aero engine gas path fault occurs.

4.3 Analysis of results

The aero engine off-gas monitoring model uses the electrostatic sensor and the signal processing circuit to acquire a weak charge signal in the pipeline of the gas-solid two phase flow device, and enable to perform continuous monitoring. Wherein, the low-pass filter circuit of the signal processing circuit has the ability to suppress high frequency noise, and has a strong amplification to low-frequency signal which is effective. Thus the effective signal is amplified, which can effectively filter out the noise. It ensures a high sensitivity, anti-interference ability and stability of the monitoring model. The output of the charge signal is within the range of 0-0.002mV and 0.01-0.025mV. Thereby effectively distinguishing the signal in the normal operation of the gas path components and the signal represents the fault type of the gas
path components. Therefore, the aero engine off-gas monitoring model has high reliability.

5 CONCLUSION

Using the aero engine off-gas monitoring model, early fault warning can be made by detecting the characteristics of signal of charged particles in the gas path, which is a potential monitoring technology. But aviation engine gas path has high flow speed, temperature, and interference, with diverse solid particles, so that enhancing the performance of the monitoring model and recognizing the signal which represents the faults of various components are the key point of development of the monitoring technology.

The future direction of the aero engine off-gas monitoring technology is as follow:
1) Further optimization of performance of the aero engine off-gas monitoring model, such as the anti-noise performance and the stable performance.
2) Further recognition of the fault in aero engine gas path, such as wear faults in blades and casing or seal component etc.

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