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A Monitoring Experiment for Gas Path Electrostatic Probe-type Sensor on Turbojet Engine

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Abstract: An electrostatic monitoring experiment was carried out on a turbojet engine with valuable induction signals. According to the measured signals monitored over a period of 137 h, combined with engine working conditions, typical signals of 216-220 phases were analyzed. The results showed that the factors which caused changes in engine exhaust electrostatic signals, were related to the properties of particles; furthermore, it was proved that the unusual exhaust particles were caused by carbon deposition from fuel spray nozzle. Therefore, under real-time monitoring of gas path with electrostatic sensor, early warning could be provided for initial fault condition as well as real-time reference for condition-based maintenance.

Key words: Turbojet engine, gas path, exhaust monitoring, electrostatic signal, probe-type sensor, carbon fault, condition-based maintenance

INTRODUCTIONS

Engine condition monitoring was the basis for aircraft safety and reliability. There had been a further progress in state management technology to realize Condition-Based Maintenance (CBM) (Roemer *et al*., 2001). As for military, with the improvement of performance of advanced fighter and the complexity of engine structure, meanwhile, under harsh conditions of high temperature, high pressure, high-speed rotation and large stress on military aircraft, there were extremely important meanings of national defense and social significance for engine condition monitoring to prevent failure. For civil aircraft, it was the precondition to ensure flight safety and reasonably formulate the maintenance plans. As a view from the prevention of failure, it was of economic significance to extend engine life (Hua, 2009).

CBM requested a higher real-time condition monitoring on engine system. The electrostatic monitoring technology which was based on gas path charged particle information, could expediently get the realization of online monitoring, moreover, it could effectively enhance the capacity of Prognostics and Health Management (PHM) (Yangming *et al*., 2008). The monitoring objects were faults of gas components, including common compressor/turbine rubbing, material peeling off, the hot-end components ablatives and nozzle carbon deposition, as well as the difficult methods to monitor faults with conventional monitoring, such as leaf rubbing and combustion chamber ablatives. The principle of this technology was that abnormal particles must be engendered once there were excessive attrition, rubbing and other anomalies occurred in gas path components, and these abnormal particles changed the level of gas path charged particle. With the electrostatic sensors monitoring gas path charged particles status online, the condition information of gas path components would be monitored to provide early warning for initial faults (Wilhelm *et al*., 2004; Sorokin and Arnold, 2004). Compared with conventional engine monitoring technology, Couch (1978) noted that the technology mentioned above could monitor the foreknowledge information and detect this information.

This study would provide significant experimental explorations for gas path electrostatic detection technology on aero engine, moreover, there would be a brand-new theoretical method and technical mean to realize online monitor and faults diagnose for engine conditions.

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PRINCIPLE OF GAS PATH ELECTROSTATIC MONITORING

Particle generation mechanism: Under normal working conditions, the main ingredients of aircraft engine emissions consisted of water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (UHC), nitrogen oxides (NO_x) and Soot particle (Wei and Chuanjun, 2005), where the local rich-oil around flame-front was the main reason to produce soot, in the conditions of high-temperature and anoxic zone, fuel was formed into carbon particles, as shown in Fig. 1.

Besides of the soot particles formed in engine working conditions, there were also two sources of particles in gas path, that was, FO (foreign objects) from inlet port and fault products from gas components. The typical attrition faults contained leaf rubbing, turbine rubbing and material peeling off, while the typical combustion ablatives included combustion chamber ablatives, hot-end components ablatives and fuel nozzle clogging. When these faults happened, there would be different types and characteristics of particles, for instance, excessive soot would emerge because of nozzle clogging, resulting in charged particle concentration increased instantly.

Particle charge mechanism: Experiments had shown that pure gas would not be charged, however, because of solid or liquid particles suspended in gas, what's more, when these particles were sprayed with high-pressured gas, there would be interactions among them, or these particles had already been charged in forming process, resulting in a high-pressure gas charged (Li *et al*., 2009).There would be particles either formed from fuel combustion or FO or faults in engine parts, these particles, which were charged in formation, elimination and friction, were similar with powder-electricity. In addition, because of fuel combustion in chamber and high temperature, there must be chemical ionizations and other physical ionizations in this region to enable particles charged. Thus, the properties of charged particles in gas path were more complex involving physical, chemical and other process.

Electrostatic monitoring principle: Similar as the principle mentioned from Wen *et al*. (2010), electrostatic monitoring system included a passive inductive sensor, signal processing circuit and acquisition system. When foreign objects with electrostatic charge (Point-charge Model Q for example) passed along the sensor, parts of the power lines formed by charge Q ended at the surface of the sensor and it would cause electronic redistribution inside the sensor to balance charge Q, thus, current came into being. In this process, charge was formed by electrostatic induction and there was not electron exchange between charge Q and the sensor. Once the charged particles left the sensor, electrons inside the sensor would be restored to the state of equilibrium (Yan *et al*., 1995). Signal processing circuit and acquisition system changed the induced charge signal into voltage signal proportionally for real-time processing (Powrie and Novis, 2006). So the electrostatic sensor model settled in this paper was by point charge, as shown in Fig. 2.

MATERIALS AND METHODS

Experimental apparatus: This experimental test was on an aviation turbojet engine test shell, in summary, it was mainly used for machine performance guarantee tests, applicable guarantee test, long test evaluation, life testing and production test. The test cell consisted of thrust-bench system, fuel supply system, electric control system and test system.

Considering of the exhaust airflow, the probe-type electrostatic sensor was installed at the distance of 30 mm from the engine tailpipe, as shown in Fig. 3. In addition, the electrostatic induction signal data were collected by data acquisition card of NI-WLS9234 with 24 bit precision, also, the data were displayed and saved into computer after collection with collection procedures by Labview, 2000 Hz.

Probe-type electrostatic sensor: Electrostatic sensor consisted of sensor electrodes, insulating medium, internal circuit and grounding terminal. Electrodes needed

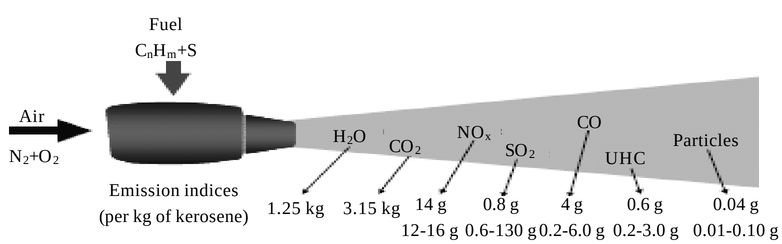

Fig. 1: Exhaust products in high temperature and anoxic zone

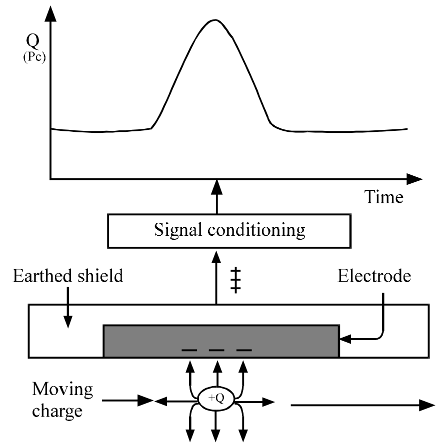

Fig. 2: Electrostatic monitoring principle

Fig. 3: Sensor installation

good conductivity and thermostability, insulating medium required good insulation material with good resistance to pressure and temperature resistance, grounding enclosure protected the internal circuit structure, meanwhile, with a good grounding to shield the external electromagnetic interference. When the charged particles flew through the measuring electrode, equal and opposite sign of charge would be inducted at the near-end and far-end of the electrostatic sensor.

The electrostatic sensor in this experiment was made into probe-typed with its probe of nickel-alloy stainless steel (diameter of 8 mm, length of 10 cm). Sensor covering made by stainless steel played a role of heat insulation and electromagnetic shielding while internal insulation material was microcrystalline-glass ceramic that could stand up to 800°C to protect the internal circuitry (the experimental engine exhaust gas temperature did not exceed 800°C under maximum state).

The signal processing circuit was made up by the following 3 parts: The first part was charge-amplification circuit of OPA129UB with low bias current (30 fA) and high input-resistance (10^{13} Ω). There was high common-mode rejection ratio (100 dB), a smaller drift (5 μV/°C) and high stability in this circuit. The second part was composed of voltage-amplification circuit of AD8221ARM with optimal common-mode rejection performance. By changing the values of RG between tube feet 2, 3 of AD8221ARM, could there be 1-1000 gain in the circuit. The third part was low-pass filter circuit of AD704 with low current noise, low input offset voltage and low input bias current. In order to enhance load capacity of filter circuit, the grounding-end of filter capacitors would be connected to the output-end of integrated operational amplifier.

Experimental method: This method was used to detect electrostatic particles in engine exhaust. The experimental engine started to test for 200 h life span in July 2011 and the electrostatic monitoring experiments were carried out during the 200 h life span test (there were an additional 40 h after 200 h, totally 240 h), each test 1 h as a stage. Electrostatic signal acquisition began with each stage and stop working to the rotor speed falling to zero. Limited by time, this electrostatic monitoring test went on from stage 100 to 240, there were total 139 stages (the first hour was removed because collection line was connected at the ground), besides, there were 137 h effective data for probe-type sensor (NO.8 and NO.10 only by circular electrostatic sensor) as well as related test-record parameters for the basis of subsequent analysis. After each test stage, the connection structure and circuit of the sensor should be checked.

Induced signal processing: Supposed q to be a point charge, a closed surface s was made around center q and radius x, according to Gauss theorem, the electrostatic field strength through s was:

$$E = \frac{q}{\varepsilon \cdot 4\pi x^2} \quad (1)$$

where, ε is $\varepsilon_0\varepsilon_r$, ε was internal dielectric constant inside s, ε_0 was dielectric constant for vacuum, ε_r was actual medium relative permittivity. Let induced charge on sensor being Q with induction area A. Due to parts of electric field lines emitted from point charge converging to sensor surface, along the Gauss surface, the flux could be expressed as:

$$AE_A \propto \frac{Q}{E} \quad (2)$$

where, E_A was electric field strength for region A, "$\propto$" meaned proportion, approximately, E_A = E at the sensor surface, by Eq. 1 and 2, there was:

$$Q \propto \frac{A \cdot q}{x^2} \quad (3)$$

Namely, induction charge Q on electrostatic sensor surface was proportional to inducing charge q and inversely proportional to the square of distance between them. Suppose induction charge on sensor probe was Q, output voltage was measured by circuit as shown in Fig. 4.

Assuming the initial state of circuit was 0, the relationship between Laplace transform U(s) of output voltage and Laplace transform Q(s) of induced charge was:

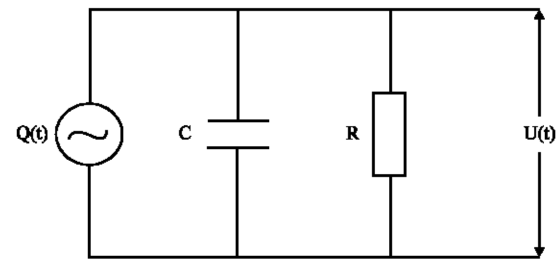

Fig. 4: Equivalent circuit of electrostatic monitoring, R: Equivalent resistance, C: Equivalent capacitance, Q: Charge

$$U(s) = R \cdot s \cdot Q(s) / (R \cdot C \cdot s + 1) \quad (4)$$

When R.C.s<<1, measuring model could be given as follow:

$$U(t) = R \cdot Q'(t) \quad (5)$$

The output signal from sensor was proportional to the first-order derivative of induction electric charge on the probe and output signal represented the change rate of induction charge. Thus, signal processing circuit changed induced charge signal from sensor into voltage signal as well as a suitable voltage levels for data acquisition and processing.

RESULTS

Background noise signals: At the phase of ignition, large amounts of positive and negative ions which were produced in the pipe suddenly, made the induced voltage on the sensor changed sharply, as shown in Fig. 5. After about 5 sec, the combustion gradually became stable and so was the induced voltage on the sensor, as shown in Fig. 6.

Typical test signals: According to the collected data, there was high sensitivity for this probe-type sensor on electrostatic signals. From engine condition, the normal background noise signals were in millivolt-level (Fig. 6) while the abnormal pulse emerged within 216-220 h of test, or even there were V-level signals (Fig. 7, Table 1) with abnormal noise from engine. After inspection, engineers found that there were large particles of carbon deposition in combustion chamber (Fig. 8). Therefore, this method could be tested

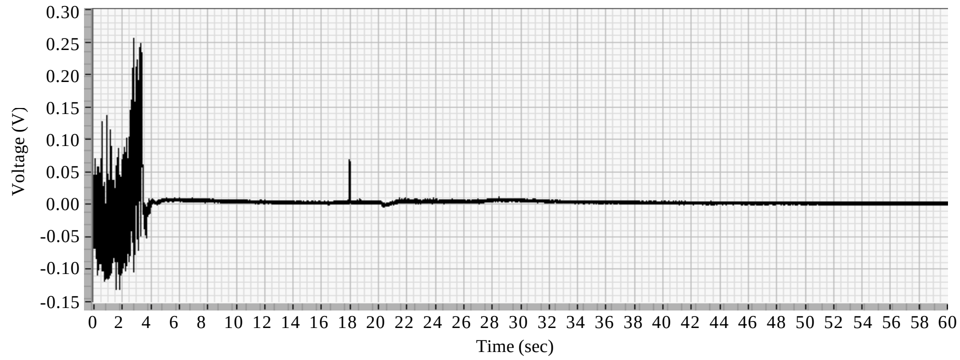

Fig. 5: Ignition phase signals

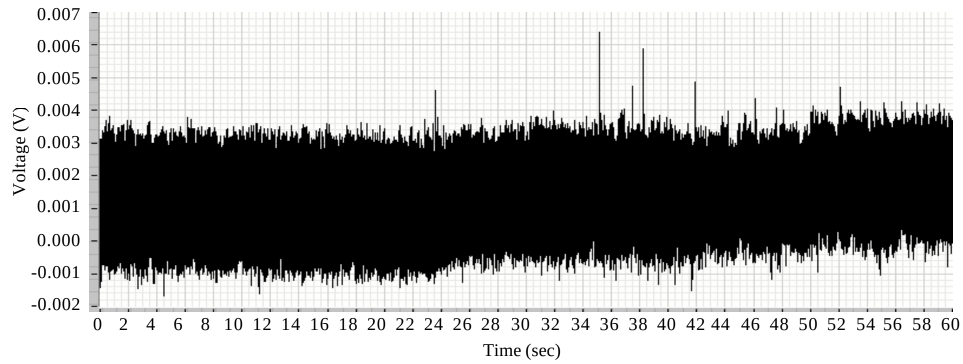

Fig. 6: Stable signals

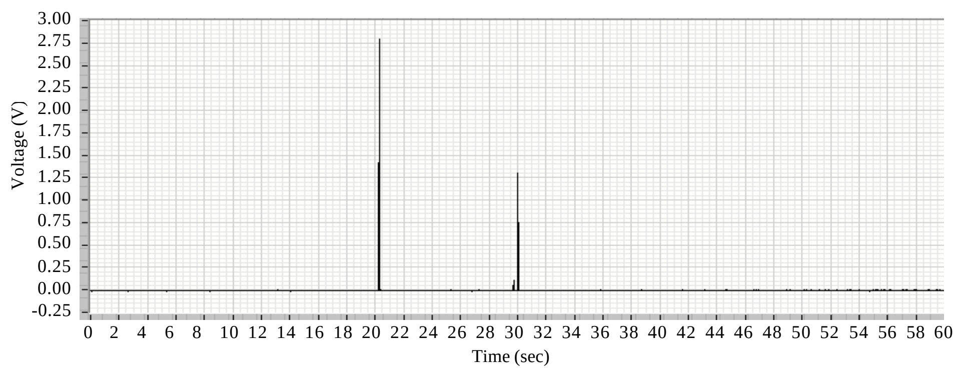

Fig. 7: Typical abnormal signals

Table 1: Abnormal signal amplitude

Date	Time	Probe-type sensor(v)
2011-12-9	09:11-09:12	0-2
2011-12-10	08:54-08:55	0-1.3
2011-12-10	14:17-14:18	0-2.75
2011-12-10	14:17-14:18	0-1.25
2011-12-11	09:09-09:10	0-0.35
2011-12-11	09:42-09:43	0-0.3
2011-12-11	09:43-09:44	0-0.2
2011-12-11	09:47-09:48	0-1.45
2011-12-11	09:56-09:57	-0.5-2
2011-12-11	09:58-09:59	0-0.15

Fig. 8: Carbon deposition from fuel spray

by real-time monitoring changes of charge level for early warning of initial fault condition.

DISCUSSION

Under engine working conditions, with self-made probe-type electrostatic sensor on experiments, discussions were given as followed:

This study crossed from theory to experiment successfully and verified the sensor validity as well as technology feasibility. From time domain signal, electrostatic monitor signal changed with output power and combustion efficiency. It was easily distinguished from background signal and fault signal.

Under normal condition, the base line of time-domain signal was maintained in millivolt- level and the normal charge of particles was 0.3-0.5 pc after signal conditioning processing to satisfied theory effect. In addition, different gas turbine working conditions referred to different particle flow and it had been found that the signal strength depended on where the sensor was located. These changes affected sensor responses.

There was little effect from sensor electrode radius to sensitivity distribution. With insulating layer thickness increased, the sensitivity distribution was more uniform, but resulted in sensitivity reduction. Electrostatic sensor probe in space corresponded to a low pass filter and signals were related to electrode axis position and charge velocity.

It was proved that the factors, which caused changes in engine exhaust electrostatic signals, were related to properties of particles. Non-metallic particles were frequently emerged in the experiment with relatively large diameter (voltage signal transformed clearly), moreover, these abnormal signals mostly appeared in the case of high-speed, possibly and they were the carbon deposition fell from fuel spray nozzle in high-speed airflow or compressor, turbine rubbed between seal materials.

After frequency analysis, there was no frequency-multiplication corresponding to rotational speed. Therefore, the abnormal ones were carbon deposition from fuel spray nozzle; meanwhile, it was sure that there were large carbon particles after engineers taking apart the engine.

Activity level was the effective value of induction charge induced on sensor in certain time interval (1 sec in this study). It was found the activity level changed simultaneously with engine working conditions. Therefore, the working condition was the main reason for changes of activity level; furthermore, it showed activity level mainly reflected the tiny charged particles of tail gas.

The activity level of No. 206 phase appeared relatively larger. The possible cause was improper installation of engine starting motor which leaded to lubricating oil leaking into gas path. The oil was inhaled into combustion chamber for combustion with high temperature air. There was some negative impact on combustion performance.

There were also some signals induced by metal particles in electrostatic monitoring with small amplitude occurred occasionally. The possible sources of these particles could be chipping from compressor blades or turbine blades, combustor materials-loss, cavitations damage. The research needs later analysis from engine disassembling report, combining abnormal signal characteristics with faults, the typical failure characteristics could be proposed.

Due to experiment conditions, this study was limited to exhaust gas monitoring, inhalation electrostatic monitoring experiment had not yet been carried out.

Combined with foreign object inhalation and exhaust particles, it would be judged whether the engine faults are caused by foreign objects.

Not only one monitoring technology was enough, though electrostatic monitoring technology obtained early fault information, the precise diagnosis also needed traditional technology supplement. Cooperated with other traditional monitoring techniques (such as vibration monitoring), multi-parameter information fusion would be carry out in future.

CONCLUSIONS

First, with working conditions changed, probe-type electrostatic sensor could not only monitor the state of gas line but also reflect the changes of engine condition and charged particles. Second, this experiment was carried out on a turbojet engine with valuable 137 h data to verify the validity and feasibility. Among them, sensor designing was the key technology. Under real aircraft engine condition, the endurance capacity of sensor was verified in high temperature and high speed flow. There would be a reference to optimize the sensor. Third, at the phase of ignition, large amounts of positive and negative ions made the induced voltage on the sensor changed sharply, with working conditions normalized, the combustion gradually became stable and so was the induced voltage. Four, from engine condition, the normal background noise signals were in millivolt-level (0.3-0.5 pc) while the abnormal pulse emerged within 216-220 h of test, or even there were V-level signals with abnormal noise from engine. Five, the particle strength was dependent upon the location of turbine exhaust path and flow properties, in addition, the sensor had a limited sensing area ,the best axial length of test probe was 80 mm in the experiment. Six, the experiments showed that the factors, which caused changes in engine exhaust electrostatic signals, were related to properties of particles. Moreover, there was no frequency-multiplication corresponding to rotational speed. It was sure the abnormal ones were carbon deposition from fuel spray nozzle. This finding provided auxiliary detection for engine life test to lower cost. The last, as a new engine monitoring technology, gas path electrostatic monitoring technology provided early warning of components faults by changes of exhaust charges. This study pointed out a clear direction for monitoring technology as well as airborne application in future.

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