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REVIEW OF PROGRESS IN THE DEVELOPMENT OF CAPACITIVE SENSORS FOR BLADE TIP CLEARANCE MEASUREMENT

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ABSTRACT

This paper describes how blade tip clearances can be measured with capacitive sensors and the right electronic devices. The design of a capacitive sensor is tightly connected to the engine environment, but also the electronic system which is used to calculate the blade tip clearance. We present two kinds of capacitive sensors : the *composite* and the *integral* sensors we developed for use in a compressor. Based on that experience we are developing and testing turbine versions of these designs. In an aero gas turbine the design aim is sensors that shall survive temperatures and vibrations as high as 1,300°C and 150 G's.

1. INTRODUCTION

Blade tip clearances in aero gas turbine have always been very important parameters to measure. For the engine performance, this clearance has to be kept to a minimum, but for the engine safety, blades should never touch the casing. The blade tip clearance changes in normal engine operations because of:

casing thermal effects,
rotor centrifugal, thermal and growth effects.

Time responses of casing and rotor effects are totally different, and this can induce large tip blade clearance variations.

Typically clearances are about 2% of blade heights (in large commercial engines this means 1 to 2.5 mm). In normal operations the clearance can range from 0 to 4% (cf. ref. 1). In modern engines an increase of 0.125 mm of the clearance in the high pressure compressor will lead to a 0.5% decrease of the compressor efficiency and an increase of the engine specific fuel consumption of 0.2%. A similar increase in the high pressure turbine will lead to an increase of the engine specific fuel consumption of 0.25% (cf. ref. 1).

It is possible to evaluate savings if the engine specific fuel consumption is reduced by 1%. Let us consider a 200 seater twin jet aircraft flying 10 hours daily. Each engine of 300 kN thrust has a specific fuel consumption of about 0.6 kg/daN.Hour. Daily, this twin engine aircraft will consume 360,000 kg of kerosene.

If savings up to 1% can be reached, thanks to a better control of tip blade clearances, the daily return could be up to 3,600 kg of kerosene.

This can be the equivalent of:

- 36 more seats (100 kg per passenger) or,
- 18% more payload or,
- 4 million US $ per year.

There is, therefore, a huge interest in developing reliable sensors to measure and provide for control of blade tip clearance.

For military engines, it is also very important to improve the knowledge of the tip blade clearance in order to take into account the engine casing deformations (high G maneuvers, exhaust gas not flowing in the engine axis).

The most promising technology seems to be capacitive sensors. These sensors have to be as small as possible in order to avoid any casing temperature distribution perturbation. Similarly, sensor air cooling should be prohibited. This means an extremely severe sensor specification in terms of temperature, pressure, vibration, corrosion, 500 hours Mean Time Between Failure (MTBF) for tests, and up to 20,000 hours MTBF for commercial in flight application.

Capacitive sensors have been used for 25 years for research and development in high pressure compressors with good accuracy and reliability. However, it is even more important to be able to measure the clearance in the high pressure turbine where there is an active control of the clearance by cooling the turbine casing. Another advantage of clearance capacitive sensors is that, except on shrouded blades, they could also be used as speed sensors, saving a good amount of weight, money and electronic circuitry.

This paper will describe the use of capacitive sensors in an aero gas turbine environment and, based on experience of compressor sensors, the developments aims and objectives for turbine sensors.

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2. TIP BLADE CLEARANCE MEASUREMENT WITH CAPACITIVE SENSORS

2.1 Capacitive sensors

Figure 1 shows how a capacitive sensor electrode can be placed in front of the passing rotor blades.

This electrode has to :
- be mechanically well assembled to the casing,
- keep the hermetic sealing of the casing,
- be electrically isolated from the ground.

Blades are electrically grounded via roller bearings. In some circumstances, an oil film can disrupt this electrical continuity. Usually, this grounding is kept through roller bearings with metallic or graphite joints.

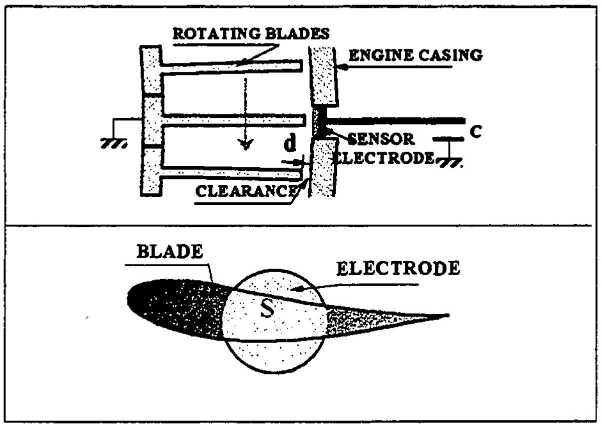

FIGURE 1 : Capacitive sensor in an aero engine

If we neglect fringe effects, each blade and the electrode form a plan condensator. The capacitance C can be calculated as follows :

$$C = \varepsilon . S / d$$

ε : gas dielectric constant
S : common blade/electrode area
d : blade to electrode distance

The gas dielectric constant is very close to 1. If a more precise value of ε is required the following formula (cf. ref. 2) can be used :

$$\varepsilon - 1 = k . P / T$$

Depending on the engine characteristics and the sensor location in the engine, a correction can be made onto the dielectric constant value. Nevertheless, this correction is quite small (less than 0.2%) and can usually be neglected (cf. ref. 10).

If we want to calculate the tip blade clearance using the capacitance, then the common blade/electrode area has to remain constant in any engine power configuration. This requires a careful evaluation of the rotor axial displacements and of the rotor and casing thermal expansions.

The size of the electrode will be a compromise between a "large" area S, which gives a "large" capacitance, and a "small" sensor to survive the engine environment and to induce as little as possible modifications of the casing temperature distribution, shape and thermal inertia.

The surface of the electrode can be either flushed to the inner casing surface or slightly recessed by 0.5 mm. To have it inside the casing can have the double advantage of avoiding any blade to sensor contact, even if blades rub the casing lining, and of increasing the tip blade electrode distance allowing the use of a flatter portion of the hyperbolic calibration curve.

Figure 2 shows a typical modern commercial engine temperature distribution. Gas temperatures, as seen by the sensor electrode, are quite high : up to 600°C in compressed air and up to 1,200°C in the turbine gases. In military engines, temperatures can be 100°C higher. The casing outer temperatures are also quite high, i.e. up to 550°C. These temperatures, as well as the pressure and vibration levels, reduce the choice of materials to be used to refractory alloys and ceramic insulators.

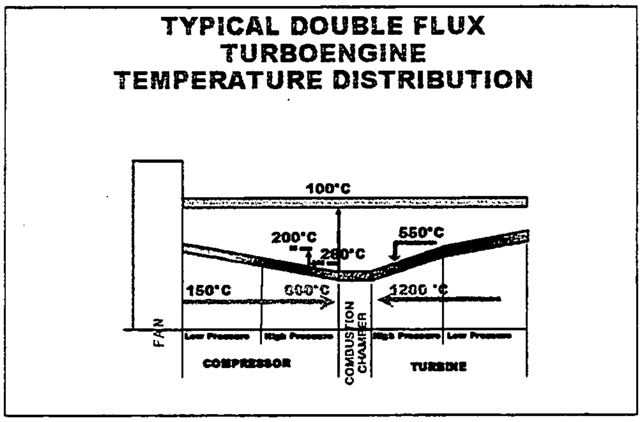

FIGURE 2 : Axial temperature distribution

Figure 3 shows a conventional design of a capacitive sensor. The electrode is brazed to a ceramic insulator to get the electrical isolation, the mechanical strength and hermetic sealing. The sensor housing is brazed, welded or screwed into a hole machined in the casing (cf. ref. 3, 4).

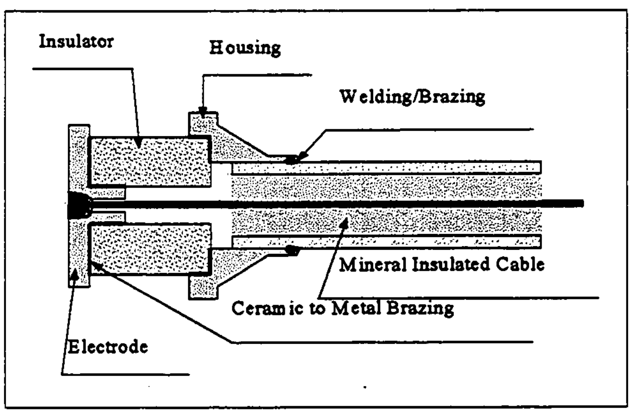

FIGURE 3 : Conventional capacitive sensor

- Digital Analog System (cf. ref. 9). DAS is unique in adding the advantage of both the analog and digital electronic circuits. It can be very precise when correctly calibrated and, from its digital part it is possible to get a lot of information in order to perform corrections (blade vibrations, elimination of electrical particles effects in dielectric...).

Every electronic system will have a different specification for the sensors : electrode size, sensor capacitance, electrical line and insulation resistance at temperature, number of conductors, coaxial/triaxial configurations. Different sizes of engines (turboprop, military, large commercial engines) will impose different sizes for the sensors : the measuring range is a function of the electrode size and the length of cabling is related to the engine size. Then, it is essential that sensors and electronic devices are developed together, even when they involve different companies and, in cooperation with engine manufacturers.

3. NEW VERSIONS OF CAPACITIVE SENSORS

We have developed two types of capacitive sensors : *composite* sensors in which the sensitive part is a ceramic and metal brazed assembly (cf. ref. 11), and *integrated* sensors in which the sensitive part is manufactured inside the MI cable itself (ref. 12). Both designs are used in testing of commercial and military engines worldwide, either in test benches or in test flights.

3.1 Compressor composite sensors

The design specification for this kind of sensor is given in table 1:

TABLE 1

temperature	-55 to 800°C
pressure	0.5 to 40 Bars
vibrations	<150 Gs, 10 to 20 kHz
MTBF	>500 Hours

This specification is typical of compressor research and development sensors. Based on our previous experience, we developed the sensor presented in Figure 5.

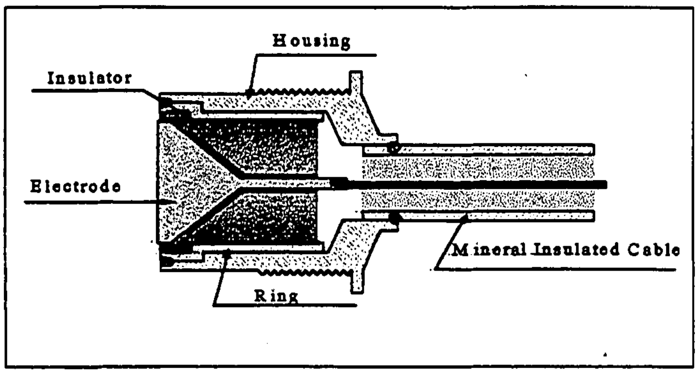

FIGURE 5 : Composite compressor capacitive sensor

The ceramic insulator is made of either aluminum oxide or beryllium oxide. The external surfaces to be brazed onto the metal parts are metallized with a Moly-Maganese ink and nickel plated. To give enough safety margin, the brazing alloy is selected to be brazed at about 1050°C. Shapes and dimensions of the metal and the ceramic parts are carefully adjusted, as well as the amount of brazing alloy and the oven temperature gradients, in order to get excellent and long lasting brazed joints and to prevent any stress accumulation.

The external surface of the ceramic insulator can be glazed to produce an extremely smooth surface to prevent its pollution.

This brazed assembly is linked to the MI cable via a metal housing and several Laser welds. The advantage of Laser welding is that we can accurately control the amount of welding energy and not overheat the welded parts at high temperature. This prevents damages of the brazing. Figure 6 shows a cross-section of a finished sensor. It can be noted that all angles are smoothed to prevent stress accumulation. The mineral insulation in the cable is densely packed and we perform a special impregnation treatment to prevent the powder from getting loose and coming out of the cable.

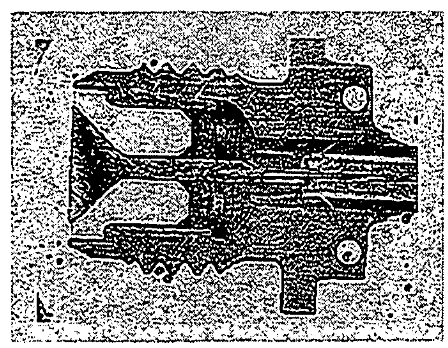

Figure 6 : Cross section of a compressor sensor

After brazing and assembly development, several prototypes were made with conventional nickel alloys but also with platinum for the electrode and ring. On three samples, we performed 50 thermal cycles from room temperature up to 800°C. The sensor heads and 30 cm of cable were placed inside an oven, and the total elapsed time at 800°C was 200 hours. The measured sensor insulation resistance remained larger than 10^6 Ohms at 800°C. At room temperature, the sensor insulation resistance dropped from 10^{12} Ohms down to over 10^7 Ohms. These values are quite acceptable. A DC system will require a minimum of 10^4 ohms; the DAS system is more tolerant (down to 10^3 ohms) but requires a low capacitance and line resistance cable.

Before installation in an engine, the mechanical strength of the sensor was tested for over tightening (almost 10 times the maximum torque), vibrations at working temperature and static load on the electrode (10 times the maximum static pressure). Tested sensors were strongly deformed, but survived the test.

3.2 Turbine composite sensor developments

Based on that experience, we are currently developing sensors able to withstand 1300°C and the same order of magnitude of pressure and vibration levels found in the compressor. Main problems are the temperature and corrosion behavior of sensor heads and the sensor insulation resistance.

The general design of the compressor sensor is kept but materials and technologies are different. For this application, the temperature specification limits the choice of brazing alloys to Palladium (melting temperature of 1555°C). This brazing temperature will exclude all nickel and iron alloys for the metal parts of the ceramic to metal assembly. The electrode and ring are made of platinum, at least for the prototypes. Platinum is a very expensive material. However, we have a good experience in brazing platinum to ceramics, and we know how to Laser weld it to nickel alloys. Due to the brazing temperature level, we have to select the ceramic material and metallisation ink. Sodern and Thermocoax did some research in that area. The best candidates for the ceramic insulator are aluminum oxide and beryllium oxide. The metallisation ink is based on a tungsten powder and has to be fired at an extremely high temperature (about 1700°C) in a wet hydrogen atmosphere.

To get a high insulation resistance for the sensor at 1300°C, the MI cable has to be of a very high integrity. The insulating ceramic powder will be either pure boron nitride or a boron nitride/magnesium oxide mix. Boron nitride has an extremely high electrical resistivity and thermal conductivity, yet it is a difficult material to work with. Moreover, boron nitride is not stable over 1000°C in oxidizing atmosphere. The selection of the mineral insulation is then made according to the exact thermal profile found around the turbine casing.

A series of qualification tests will be performed on prototypes, like thermal cycling and vibration testing, before they are installed in a turbine of a European military engine by the end of 1996.

3.3 Compressor integrated sensors

For this kind of sensors the electrode diameter is 1.5 mm and smaller. Figure 8 shows an integrated capacitive sensor.

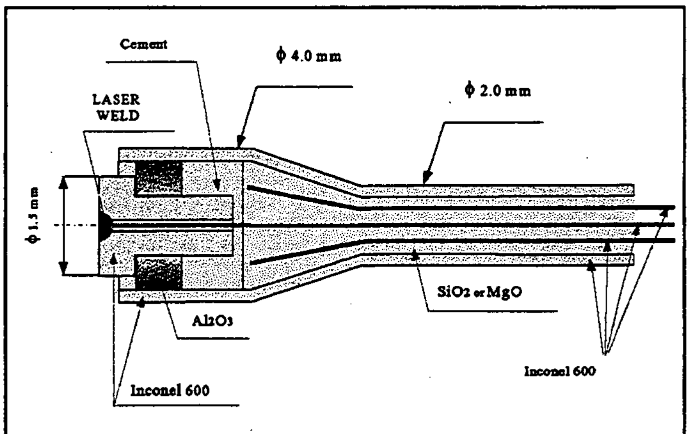

FIGURE 8 : Integrated compressor capacitive sensor

The sensor head is built inside a 4mm diameter MI cable. To allow flexibility and ease the sensor installation, the MI cable diameter is reduced down to 2 mm. In this particular application, the electronic system connected to the sensor is a capacitance bridge (cf. ref. 7) which requires a 3 conductor cable. The sensor electrode is hollow and one of the center conductors is Laser welded onto the electrode's outside surface. The other 2 conductors are shortened inside the cable itself . The electrode is centered inside the sensor housing with an aluminum oxide ring. The inner sensor components are held in place by a high-temperature cement and by the conductor to electrode welding. Sensors are submitted to a special impregnation treatment to make them less sensitive to air moisture and baked at 800°C.

Before to be used in an engine compressor, prototypes were extensively tested temperature wise and vibration wise. These sensors are used in research and development of compressors of small and medium size engines. For example, they were installed for the testing of the JPATS aircraft engine for water ingestion and high G maneuvers.

3.4 Turbine integrated sensor developments

Development of the turbine sensor was based on the compressor design with the following requirements :

- the overall dimensions should remain the same,
- the alloys facing the turbine gases should be refractory alloys, better than Inconel 600,
- no welding should be in contact with the turbine gases to avoid corrosion,
- the electrode should be enclosed inside a metallic housing, to prevent any particle to fall into the engine in case of a problem,
- all materials included in the manufacturing of the sensor should withstand a temperature of 1300°C.

The external dimensions are exactly the same as the one's of the compressor sensor. A cavity is made inside the outside sheath and 2 of the 3 conductors are shortened to remain ungrounded.

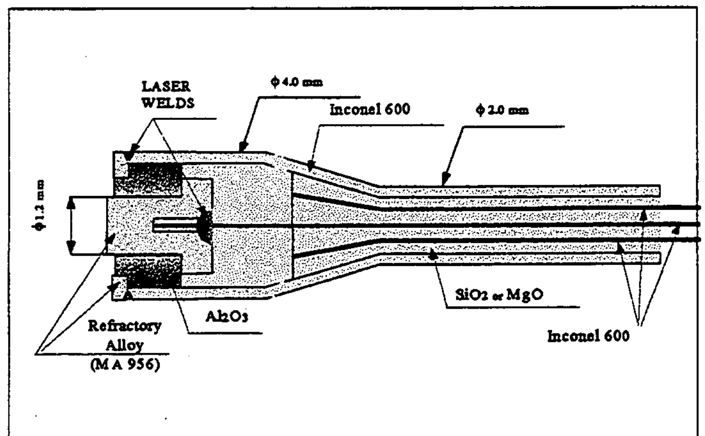

FIGURE 9 : Integrated turbine capacitive sensor

The electrode is slid over the remaining center conductor and Laser welded to it. This welding is done through 2 small holes machined in the sensor outer sheath. The electrode diameter is larger inside the sensor than outside, preventing it from coming out. A ring of refractory alloy, for example MA956, is Laser welded onto the sheath in order to protect it against corrosion and to prevent the inside components (electrode and bead) from coming out of the sensor. Then, all gaps inside the sensors are filled with a very high temperature cement and baked in order to hold firmly in place all components and resist vibrations.

After development of the turbine sensor design and manufacturing techniques, high temperature internal qualification tests were conducted. Two sensors were installed inside a high temperature tubular furnace. Sensor heads were placed in the middle of the hot section of the furnace.

Temperature cycling was set as follows :
- heating up at 5°C/min
- constant temperature for 30 min,
- cooling down at 11°C/min.

The test program was set to 50 cycles at 1000°C, plus 50 cycles at 1100°C, plus 50 cycles at 1200°C and as many cycles as possible at 1300°C. This temperature cycling test is more severe than what sensors would experience in a turbine. Due to the test furnace length, about 10 cm of sensor are exposed to the test temperatures, and 20 cm of sensor are exposed to temperature between 500°C and the test temperature. At temperatures higher than 1100°C Inconel starts to corrode very fast in air. Outside of a real turbine the thermal gradient is far more steep and much less of sensor is exposed to very high temperature.

A very important characteristic of the sensor is the Insulation Resistance (IR). At room temperatures, new sensors have IR larger than 10^{10} Ohms. Electronic systems can operate with sensors IR as low as 10^3 Ohms.

TABLE 2

Cycle Temp.	Number of cycles	High temp. IR	Room temp. IR
1000°C	50	>10^4 Ohms	>2.10^8 Ohms
1100°C	50	>7.10^3 Ohms	>10^8 Ohms
1200°C	50	>4.10^3 Ohms	>10^7 Ohms
1300°C	15	>10^3 Ohms	

After the 1200°C cycles sensors did exhibit some signs of degradation, mainly corrosion of the Inconel 600 sheath. Some swelling of one sensor can be noticed and some play between the aluminum oxide bead and the sheath.

After the 1300°C cycles sensors were damaged. However, it should be noted that only the Inconel 600 portion of the sensor exposed to 1300°C was deeply corroded, not the refractory alloy electrode or ring. The welding survived the high temperature cycling without any problem. Cross sections of sensors were examined under optical and acoustic microscopes. From this testing we noticed a very good behavior of the refractory components used in the sensor design.

Sensors were heated at 870°C and vibration tested up to 3,000 Gs at 10 kHz. In these conditions, it was found that the inner aluminum oxide bead began to extrude through the MA956 ring.

4. CONCLUSIONS

Our experience shows that compressors can be safely instrumented with capacitive sensors for accurate blade tip clearance measurements with various sensor designs and electronic circuits. Compressor sensors can survive at least several hundred hours of operation without failure. Due to the very limited turbine sensor testing, it is too early to give any reliable information on turbine sensors' MTBF.

Nevertheless, much more development efforts will have to be made before capacitive sensors can be installed in commercial flights with MTBF in the range of 20,000 hours and incorporated in the engine FADEC (Full Authority Digital Engine Computer) for an active turbine blade tip clearance control.

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