

# Blade Tip Clearance Sensors for Use in Engine Health Monitoring Applications

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## ABSTRACT

Blade tip clearance is a key design parameter for gas turbine designers. This parameter is often measured during engine testing and development phases as part of design validation but has yet to be utilized during normal engine fleet operation. Although blade tip clearance measurements are often mentioned for fleet operation in the context of active clearance control, the use of blade tip clearance measurements can provide an additional benefit for engine health monitoring. This paper explores the use of blade tip clearance sensors for engine condition monitoring of hot section blades. Blade tip clearance, especially in the first stage turbine, has an impact on exhaust gas temperature. The use of tip clearance measurements can provide supplementary information to traditional EGT measurements by providing a direct measurement of wear on the blade tips. In addition, blade creep and cracking can be measured and tracked if the sensors are able to provide clearance values of individual blades. Broken or missing blades can be identified allowing corrective action be taken in advance of normal inspection intervals. In order to enable health monitoring applications, blade tip clearance sensors must be survivable, repeatable, and provide high fidelity data. This paper discusses a microwave blade tip clearance sensor and discusses some of the key sensor attributes needed for successful health monitoring.

**CITATION:** Geisheimer, J., Kwapisz, D., Holst, T., and Hafner, M., "Blade Tip Clearance Sensors for Use in Engine Health Monitoring Applications," *SAE Int. J. Aerosp.* 6(2):2013, doi:10.4271/2013-01-2145.

## INTRODUCTION

Blade health monitoring continues to gain interest as a means of assessing the health of turbine airfoils in aerospace and ground-based gas turbine engines in fleet operation. Many types of blade sensors are used throughout the design validation process of new engines that would theoretically provide information for blade health monitoring. However, most of these sensors are either too difficult to use or do not have sufficient survivability to monitor blades throughout the operational life of the engine.

Two common blade tip measurement sensors used during engine development activities that provide information related to blade vibration and blade tip clearance are described in [1]. Blade vibration measurements are important to know so that the engine designer may avoid high cycle fatigue conditions, which can cause cracking and blade failures, most often in compressor stages.[2] Tip clearance measurements are used during design validation to determine the operating clearances. It is desirable to have the blade tip clearances as close as possible to the case, without touching, in order to obtain the highest possible efficiency.[3]

In the turbine section of the engine, the blades tend to be thicker and more robust to blade vibration and high cycle fatigue than compressor blades. However, the turbine blades must operate at extremely high gas path temperatures. The combined effects of high temperatures and forces on the blades can result in degradation due to creep fatigue.[4] Other damaging effects such as blade root cracking[5] [6] can occur within the turbine as well.

Active clearance control technologies are available on a variety of industrial and aerospace turbines and currently operate on an open loop control based on models and various existing measurements on the engine. Industry continues to have a large interest in bringing blade tip clearance sensors within production engines in an attempt to close the control loop and gain improved engine efficiency. [7] The highest efficiency gains can be obtained by controlling the tip clearance in the first several turbine stages where the most amount of work is being extracted out of the gas stream. However, this is also the hottest area of the engine and the most difficult area to place sensors.

As engine OEMs work to gain further efficiency from the engine and closed loop clearance control becomes viable on

production engines, the same data can be used for engine health monitoring as well.

One of the biggest challenges for any tip clearance sensor is long term survivability. Due to the high temperatures within the turbine, the components in this area are made of expensive alloys, have ceramic coatings and complicated cooling passages since the gas path temperatures normally exceed the melting points of the metals. Any sensors operating in this area must be made of a similar construction.

Capacitance, optical, and microwave sensors are typically used within the turbine for engine design validation and test applications. Often, probes must be actively cooled in order for them to survive, even for short periods of time.

This paper discusses a microwave clearance sensor that was originally developed for active clearance control applications and designed for long term operation and how that sensor might be applied to health monitoring applications within the turbine.

The first section will give an overview of the microwave sensor including the measurement principle and probe. The second section will discuss the key sensor parameters needed for health monitoring applications including individual blade measurements, sensitivity, repeatability, linearity, and accuracy. The third section discusses example microwave clearance measurements from the laboratory and engine operation. The fourth section discusses how a microwave clearance sensor might be correlated with exhaust gas temperature in order to improve blade wear condition monitoring and the final section discusses clearance measurements correlated to blade creep fatigue and blade cracking.

## MICROWAVE SENSOR OVERVIEW

### Measurement Principle

The microwave blade tip clearance sensor presented is based on a phase measurement principle. A continuous-wave microwave signal is generated within the microwave electronics and transmitted through a coaxial cable to the probe (Figure 1). The probe serves as an antenna guiding the continuous-wave into the space between the casing and the bladed rotor. The probe serves as both a transmitter and receiver, capturing the microwaves reflected back to the blade tip, which is then measured by the electronics.

A vector mixer architecture is used to compare the received signal to an internal reference and to reconstruct a phase measurement. The phase between the transmitted and the reflected signals is proportional to the distance between the probe and the blade tips. The conversion between the measured phase  $\varphi$  and the associated clearance  $\delta$  is given by Eq. (1) and depends on the wavelength  $\lambda$  of the microwave signal. Compared to other technologies, this relationship is linear and much easier to calibrate via sensitivity and offset corrections.

$$\delta = \frac{\varphi}{4\pi} \cdot \lambda \quad (1)$$

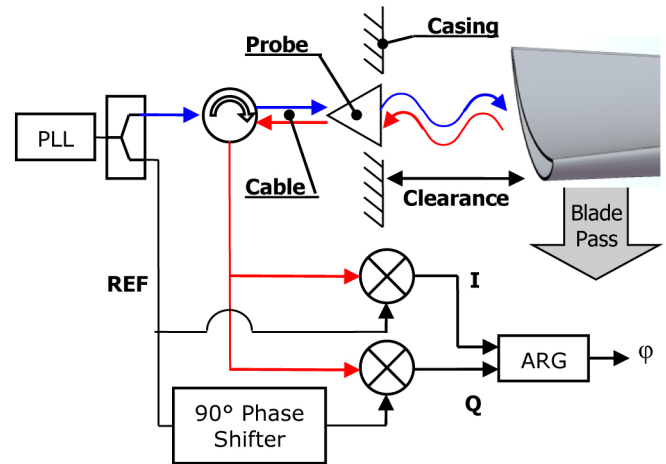


Figure 1. Microwave Blade Tip Clearance system overview.

### Microwave Probe

The microwave probe serves as an antenna optimized to transmit at a defined frequency with a given bandwidth. This antenna is packaged into a hermetic sealed body with an integral mineral cable. This probe construction is made with materials chosen for high temperature survivability and long term operation in the harsh environment of gas turbines.

Two versions of the microwave system have been developed. The first one uses a frequency in the 6 GHz band and has a measurement range of 25 mm and a probe diameter of 14 mm (Figure 2). It is suited for large frame gas turbines. The second one uses a frequency in the 24 GHz band for a measurement range of 6 mm and a probe diameter of 8.5 mm. It is preferably used with small blades in aviation or aero-derivative gas turbines.



Figure 2. 6 GHz microwave probe.

The probe installation requires an opening through the casing such that the probe tip has a direct view of the rotor and its blade tips. A ceramic window on the probe tip allows the microwave signal to transmit to the blade. A retaining ring ensures that this ceramic window does not fall into the gas path.

Depending on the engine construction, the integration into the engine can be complex. Normally, the installation in the turbine section has more constraints due to the high

temperatures and to ensure proper sealing between several casing layers, which can move relative to each other. Figure 3 shows an example of probe mounting in the turbine section of an aero engine with two casing layers. The probe tip is usually installed flush or recessed from the casing inner surface to ensure no contact with the blades even during a rub event. An example of a probe installed on an engine is shown in Figure 4.

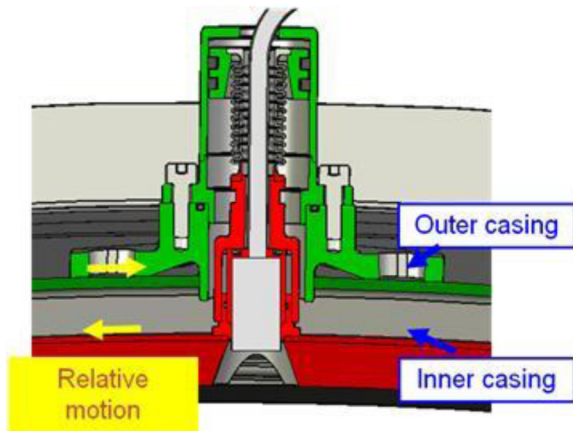


Figure 3. Probe mounting on the turbine.



Figure 4. Probe installed on engine.

The important parameter for the probe installation is the position of the probe relative to the blade tips as the probe measures what is directly underneath it. It is not always possible to install the probe at the desired location due to piping or mechanical constraints. Typically, the rotor moves axially due to thermal dilatation and aerodynamic forces and therefore the blade tips move in the axial direction with respect to the casing. This is normally a known parameter and taken into account during the probe mounting.

## CLEARANCE MEASUREMENT REQUIREMENTS FOR ENGINE CONDITION MONITORING

### Individual Blade Measurements

To perform blade health monitoring, the ability to measure individual blades is key. Many types of tip clearance

sensors perform a large amount of averaging or low pass filtering, resulting in an output signal of the average blade tip clearance.

Damage to blades will often be manifested as dimensional changes reflected in the blade tip clearance. Therefore, it is important for any clearance measurement sensor used for engine health monitoring to measure the individual blade clearances in order to assess the damage at the blade level. If a single blade was damaged, then sensors which give a composite average or highly filtered output signal would average this damage into the rest of the waveforms, making the damage virtually undetectable.

However, extracting individual waveforms, processing, and keeping track of their individual clearances can often take a large amount of computational power. The microwave sensor described in this paper runs a variety of digital signal processing algorithms to find the individual blade peaks and then extract the individual blade tip clearance.

The tips of turbine blades often have “pockets” and other complex geometries, such as those shown in Figure 5, that can make detection of the correct portion of the blade tip more challenging.

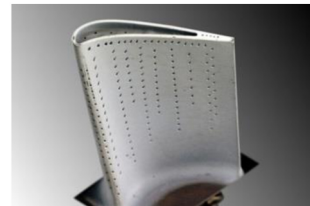


Figure 5. Example turbine blade.

In addition, to track and trend the same blade over time, it is important to identify specific blades. This is normally done with a once per revolution signal that provides a phase reference. However, the phase reference is not always reliable as the sensor is often located at one end of the turbine, far away from the first stage turbine. It is not uncommon for torque in the shaft to cause the first blade that appears after the once per revolution signal to shift by one or two blades between engine startup and full power. This normally means that some type of blade correlation algorithm is needed in order to examine the pattern of blade tip clearances and remove this effect.

Experience to date has shown that blades are typically not all at the same length, and thus are not all at the same clearance. There is a normal variability of turbine blade heights due to machining tolerances, how the blade root sits within the disk, differences in cooling passages resulting in some blades that are hotter and therefore longer, as well as different amounts of blade untwist. An example blade tip clearance pattern is shown in Figure 6.

This pattern does not change much from revolution to revolution and therefore, can be used as a “baseline” to track