

Testing of a Microwave Blade Tip Clearance Sensor at the NASA Glenn Research Center

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The development of new active tip clearance control and structural health monitoring schemes in turbine engines and other types of rotating machinery requires sensors that are highly accurate and can operate in a high temperature environment. The use of a microwave sensor to acquire blade tip clearance and tip timing measurements is being explored at the NASA Glenn Research Center. The microwave blade tip clearance sensor works on principles that are very similar to a short range radar system. The sensor sends a continuous microwave signal towards a target and measures the reflected signal. The phase difference of the reflected signal is directly proportional to the distance between the sensor and the target being measured. This type of sensor is beneficial in that it has the ability to operate at extremely high temperatures and is unaffected by contaminants that may be present in turbine engines. The use of microwave sensors for this application is a new concept. Techniques on calibrating the sensors along with installation effects are not well quantified as they are for other sensor technologies. Developing calibration techniques and evaluating installation effects are essential in using these sensors to make tip clearance and tip timing measurements. As a means of better understanding these issues, the microwave sensors were used on a bench top calibration rig, a large axial vane fan, and a turbofan. Background on the microwave tip clearance sensor, an overview of their calibration, and the results from their use on the axial vane fan and the turbofan will be presented in this paper.

I. Introduction

The active control and minimization of the gap between the rotating turbine blades and the stationary case of gas turbine engines is being investigated as a means of increasing engine efficiency, reducing fuel consumption, reducing emissions, and increasing engine service life¹. In addition, the ability to monitor the structural health of the rotating components, especially in the hot sections of turbine engines, is of major interest to the aero community in improving engine safety and reliability. Both of these concepts require the development of sensors that are reliable and can operate in the harsh conditions that exist in a turbine engine. Under the NASA Fundamental Aeronautics and the NASA Aviation Safety Programs microwave sensor technology is being explored at the Glenn Research Center as a means of making high temperature non-contact tip clearance and tip timing measurements for use in active clearance control, structural health monitoring, and other close tolerance control applications associated with turbine engines and rotating machinery.

This paper discusses testing and evaluation that has been accomplished during the last year using a microwave sensor system that was developed and purchased under NASA's Small Business Innovation Research (SBIR) Program from Radatec, Inc. (currently Vibro-Meter, SA). Background on the microwave sensor system and its recent use on a calibration rig, an axial vane fan, and a NASA turbofan are discussed in this paper.

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II. Sensor Background and System Description

The microwave tip clearance sensor system that is currently being used at the NASA Glenn Research Center was developed by Radatec, Inc. (Currently Vibro-Meter, SA) through NASA's Small Business Innovation Research Program (SBIR) under a phase II contract that was awarded in 2002. Work on the sensor continued in 2004–2005 as part of NASA's Ultra Efficient Engine Technology (UEET) Program. In late 2006, the system was delivered to the Glenn Research Center as part of a Phase III SBIR commercialization contract. This system currently has two sensor channels along with four high temperature probes. The microwave tip clearance sensor system works on principles that are similar to a short range radar system. The tip clearance probe is both a transmitting and receiving antenna. The sensor emits a continuous microwave signal and measures the signal that is reflected off the metallic target, which in this case is a rotating blade. The motion of the blade phase modulates the reflected signal. This reflected signal is compared to an internal reference signal and the phase difference directly corresponds to the distance to the blade. More detailed information on the sensor's theory of operation can be found in Refs. 2–5.

The high temperature tip clearance probe shown in Fig. 1 is approximately 14 mm in diameter and 26 mm long. It contains the transmitting and receiving antenna and is designed to be installed in the casing of the engine where it can measure the radial clearance between it and the turbine blade tips. The probe is made of high temperature material and is designed to withstand temperatures up to 900 °C uncooled, 1200 °C with cooling air. The associated sensor electronics and data acquisition system for the microwave tip clearance system are shown in Fig. 2. This hardware contains the RF generator, RF detector, and all of the associated hardware required to generate, measure, and condition the microwave signals. It also contains a rack-mounted PC that runs the data acquisition and display software. It is intended that the sensor electronics be located away from the engine in an environmentally benign area. The probes are connected to the electronics using a microwave rated co-axial cable. Cable distances up to 15 m can be currently supported between the probes and the sensor electronics. The data acquisition computer is connected to the sensor electronics through a network switch. This computer can be remotely located away from the sensor electronics to an area such as a control room using a CAT5E connection.

The existing microwave system operates at 5.8 GHz and with the current probes can measure clearance distances up to ~25 mm (i.e., one-half the radiating wavelength). This technology has an ultimate goal of obtaining accuracies approaching 25 μm . This is in the process of being developed in the next generation of probes. More on the system's use and observed accuracies with the current probes are discussed in this paper.

As indicated earlier, NASA has several programs interested in the development and use of sensors that can make accurate tip clearance and timing measurements in the harsh environment associated with gas turbine engines. The microwave probe's ability to operate at high temperature and see through contaminants that are

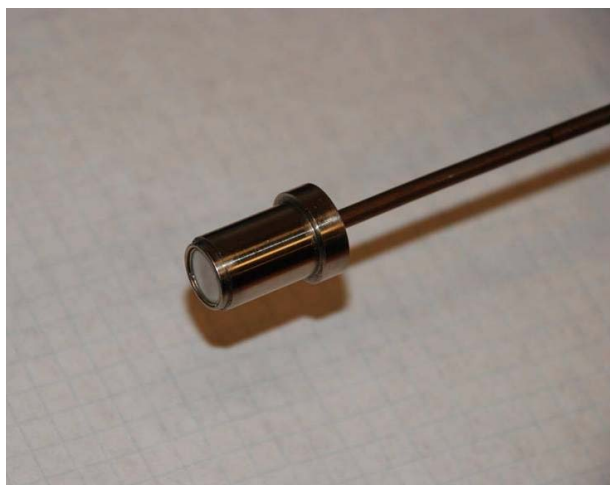


Figure 1. Microwave tip clearance probe.



Figure 2. Microwave sensor electronics and data computer.

present in a turbine engine is a major discriminator between it and other technologies. These sensors were originally being targeted for use in an active clearance control concept that was being developed at the Glenn Research Center⁶. In addition, there is interest in using these sensors to make structural health measurements by either using tip clearance to monitor blade growth and wear or using tip timing to monitor variations in movements between blades. Over the last year a series of experiments have been undertaken at the Glenn Research Center as a means to better understand this technology and evaluate its capabilities. The near-term goal of the project is to evaluate the sensors ability to make tip clearance and timing measurements on rotating machinery. The long-term project goal is to use these sensors in an actual aero engine at high temperature conditions. This is currently being targeted to occur in the 2009 to 2010 timeframe.

III. Calibration Experiment

The first experiment that was accomplished with the microwave tip clearance system was the calibration and evaluation of the probes using a bench top calibration rig. Like other sensor technologies, measurements made using the microwave sensors were very specific to the geometry of the blade being measured. The sensor made an average measurement of the spot size that was cast on the blade. To obtain accurate and useful results, this average measurement needed to be mapped to the actual minimum clearance between the target blade and the sensor. This was done by calibrating the sensor against the blade geometry that it was intended to be used on for making tip clearance measurements. Since the use of microwave sensors is an emerging technology, techniques on calibration and installation effects were not fully quantified as they were for older technologies. The main goal of this experiment was to develop the infrastructure and techniques to calibrate the probes for use on experiments at the Glenn Research Center. In addition, the calibration rig provided a good venue to evaluate the probe's accuracy and understand any effects associated with the probe's installation.

The calibration rig setup shown in Fig. 3 consists of a rotary stage and a linear stage controlled by a programmable motion controller. The candidate blade for the calibration was mounted on the rotary table where it could be operated up to 300 RPM. The microwave probe was mounted on the linear stage where it could be moved to a desired distance from the blade tip for calibration. This linear table used an optical encoder with an accuracy of 4 μm for position indication. A typical calibration involves installing the probe and blade on the stages at a known baseline distance apart from each other using a precision metric gauge block. Typically, the baseline distance chosen was the largest distance for the calibration. Once this baseline distance was established, the setup was confirmed by moving the linear stage over the entire calibration range and verifying the distances between the blade and sensor using the precision gauge blocks at several distance settings. The metric gauge blocks used had an uncertainty of 0.14 μm . Once the setup was confirmed the blade was operated at 200 RPM using the rotary stage and the probe was moved to the desired gap distances using the linear stage and encoder. At each desired distance, the "measured" or uncorrected reading was recorded. This was done over the entire calibration range.

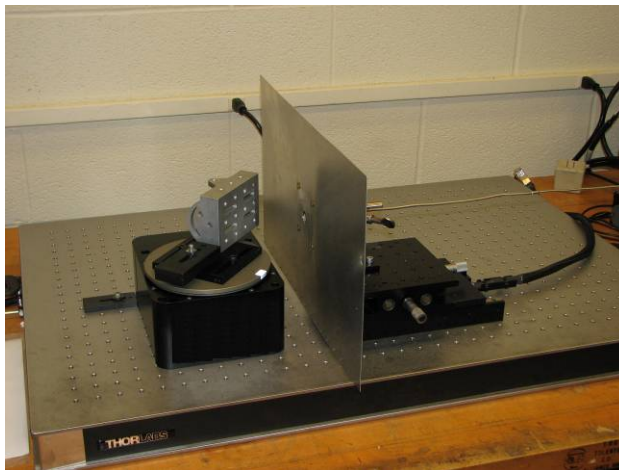


Figure 3. Microwave Probe Calibration Rig.

The following items need to be noted when using and calibrating the microwave probes. First, the blade needs to be spinning in order for the microwave clearance system to detect and measure the clearance. The system operates on the principle of extracting the phase modulation from the reflected signal that is caused by the motion of the blade. To measure the clearance it needs to see a target that is moving. Second, the microwave probes were designed to be mounted in a metallic casing or reference plane. This allows the microwave field to emit properly from the face of the sensor. The current 5.8 GHz sensors were designed to be recessed by 0.50 mm in an engine or fan casing. For the calibrations conducted in this experiment, a 265- \times 425-mm metal sheet was used to simulate the

fan casing for the probe's installation. Third, for the calibration it is desirable to match the physical set-up of the actual installation on the engine or test article as much as possible. This is very similar to what was done for other tip clearance sensor technologies. This involves matching the probe installation depth, simulating the engine casing as much as possible, and matching the blade angle as best that can be done. One additional feature that the microwave probes have is the field emitted by the probe has a polarity. This feature can be used as an extra adjustment in improving the quality of the signal based on the size of blades and overall geometry. To maximize the amount of signal that was sent out and collected from the blade, the face of the probe was aligned so its polarity was in-line or parallel with the length of the blade tip that it was measuring. To minimize the amount of signal that was sent out and collected from the blade the probe was rotated so its polarity was perpendicular to the length of the blade tip. Generally, it is recommended by the manufacturer that a parallel alignment be used for blades that are much thinner than the diameter of the probe and a perpendicular alignment be used for blades that are thicker than the diameter of the probe. Generally, the best response may fall somewhere between. The probe alignment is a trade off that needs to be made based on the application. As with the previous installation parameters, when calibrating the probes it is critical to duplicate the alignment that is used in the actual engine or test rig. During this calibration experiment the probe's polarity was varied as a means of assessing and understanding its effect.

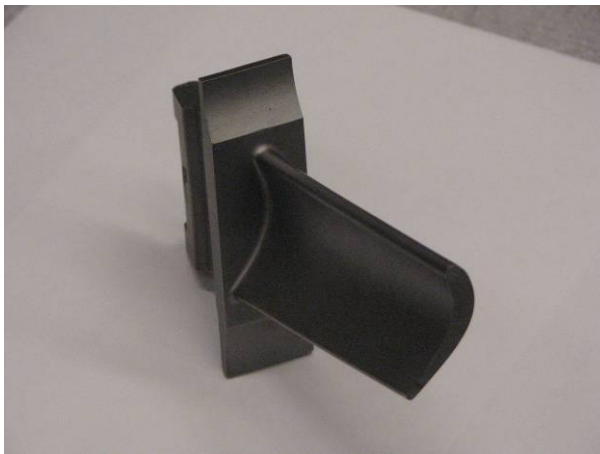


Figure 4. Compressor blade used for calibration.

For this experiment, calibration was done against two different blade geometries. The first geometry that was tested was a relatively thin first stage compressor blade. This blade shown in Fig. 4 is ~105 mm long, ~6 mm thick at its widest point, and has a chord length of ~37 mm. This blade was chosen to see how well the probes would calibrate against a blade's geometry that was smaller than the diameter of the probe. The second geometry tested was a flat box. This box, shown mounted on the rotary stage in Fig. 3, was ~26 mm thick, ~76 mm high, and ~107 mm long. It was chosen to simulate a blade that was thicker than the diameter of the probes. In addition, it mimicked the thickness of the blades of an axial vane fan that the probes were used on to measure tip clearances. The results of the experiment on the axial vane fan will be discussed in section IV of this paper.

The calibration curve for a microwave probe using the thin compressor blade is shown in Fig. 5. The y-axis is the "measured" or uncorrected clearance reading that was acquired from the probe. The x-axis is the actual clearance. It represents the distance between the simulated fan casing, with sensor, and the tip of the blade. The calibration was done over a range of 0.5 to 13.0 mm. The resulting curve is a third-order polynomial and has fairly good sensitivity at clearances above 2 mm. At clearances lower than 2 mm, the response flattens out and the sensor becomes less sensitive. This effect is believed to be caused by the near field properties of the probe's antenna and its interaction with the geometry of the relatively thin blade. The curve observed in Fig. 5 was a typical response when using the probes on a thin blade when compared to the probes diameter. For this calibration the sensor's polarity was aligned to be parallel with the length of the blade tip to maximize the amount of energy reflected from the blade.

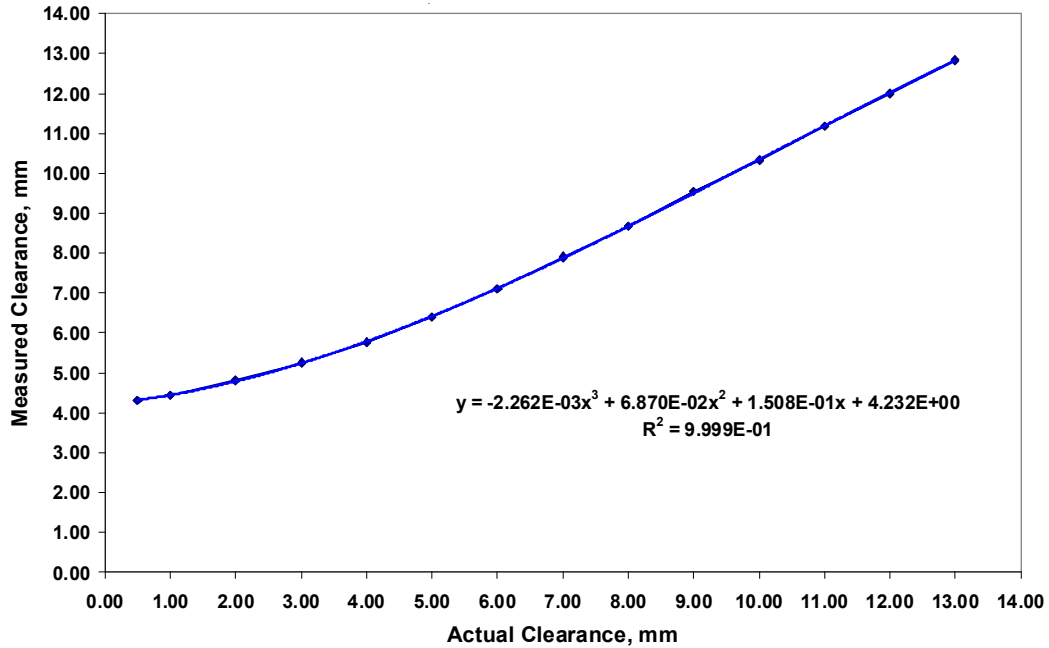


Figure 5. Calibration curve for thin blade.

Figure 6 shows the calibration curve for the same probe against the simulated thick blade. This calibration was undertaken as a means of capturing the necessary correction data for measuring the tip clearances on a large axial vane located at the NASA Glenn Research Center. As in the previous case, the y-axis is the “measured” or uncorrected clearance reading that was acquired from the probe. The x-axis is the actual clearance distance between the simulated fan casing, with sensor, and the tip of the blade. The calibration was done over a range of 1.0 to 13.0

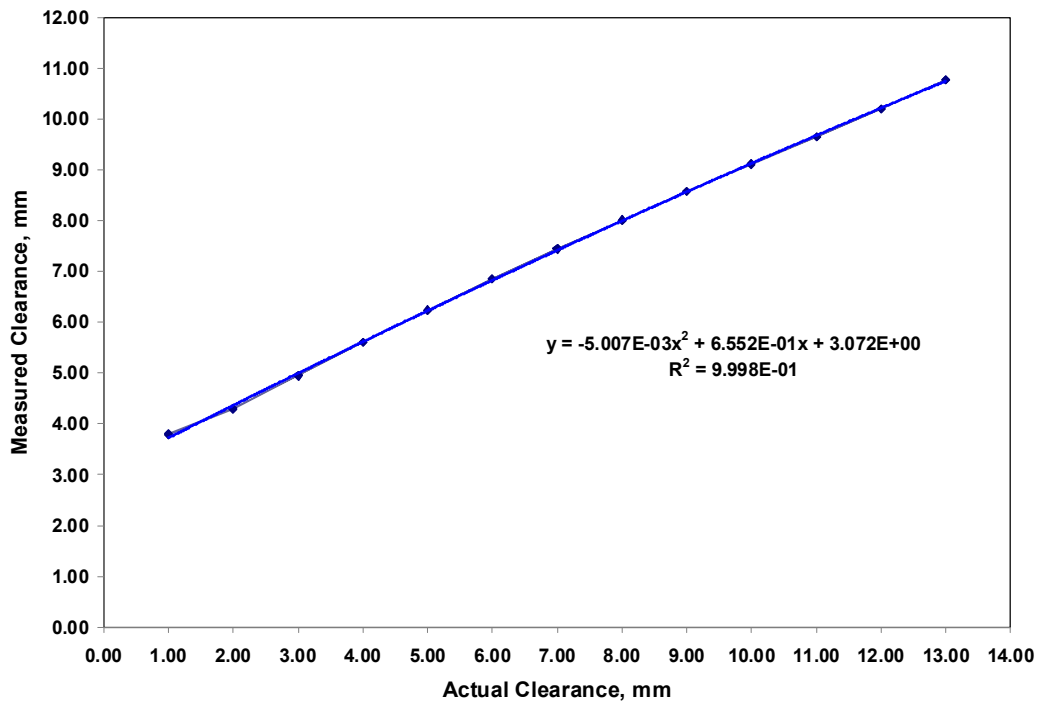


Figure 6. Calibration curve for simulated thick blade.

mm. The resulting curve is a second-order polynomial and has a relatively constant sensitivity over the entire range. For this calibration the sensor's polarity was aligned perpendicular to the length of the blade tip. A similar shaped curve, with slightly different values, was observed for the calibration where the probe's polarity was aligned parallel to the thick blade's tip. The curve reported in Fig. 6 was a typical response when using the probes against a blade whose thickness was of the same order of magnitude or greater than the diameter of the probe. As a means of evaluating the overall accuracy and repeatability associated with the calibrations on the thick blade, both the probe and blade were reset and the experiments were repeated across the entire range with the clearance corrections applied to the measurements. The worst case error that was observed between the actual distance and the corrected distance measured by the sensor in these verification tests was ~ 0.15 mm. It is believed that a portion of this error can be attributed to inaccuracies and biases associated with the calibration setup. In subsequent calibrations on a turbofan blade, improvements in the calibration setup resulted in errors that were much smaller. This calibration is presented in section V of this paper. In summary the calibrations against the thin blade and the simulated thick blade were primarily undertaken as a means to better understand the probes and develop techniques for their calibration. These objectives were achieved and the probes were successfully calibrated against two blade geometries.

IV. Axial Vane Fan Experiment

The second experiment was to use a sensor to make tip clearance measurements on a large axial vane fan located at the NASA Glenn Research Center's 10- by 10-Foot Supersonic Wind Tunnel (10 \times 10 SWT) Facility. The purpose of this experiment was to acquire experience in using the sensors on an actual piece of rotating machinery. It was also intended as a means to evaluate how well the calibrations accomplished in the laboratory transferred into an actual use in the field. The axial vane fan that was used is shown in Fig. 7. It is part of the 10 \times 10 SWT's infrastructure and is located in the tunnel's Air Dryer Building⁷. It is one of eight fans that are used to heat, dry, and cool the wind tunnel's alumina beds. The fan is ~ 1.8 M in diameter and has 16 blades. The blades are ~ 362 mm long, with a chord length of ~ 267 mm and a maximum thickness of ~ 26 mm at the midchord position. Provisions were made for the installation of two probes 90 degrees apart in the fan's casing at the midchord position of the blades. A calibrated microwave tip clearance probe was installed in one of the locations. A picture of a probe installed in the fan is shown in Fig. 8.

Data was acquired over several operations of the vane fan varying the configuration and setup of the sensors. Data was taken with the probe's polarity aligned both parallel and perpendicular to the length of the blade tip in order to assess the effect of the sensor's alignment on the measurement. In addition, data was taken in the synchronous, asynchronous, corrected, and uncorrected data modes as a means to better understand the system's settings and sensor capabilities. Only a summary of the results of the test runs for this experiment will be included in this paper.



Figure 7. Axial Vane Fan located at the 10x10 SWT.



Figure 8. Probe installation on the axial vane fan.

A time history of the average and minimum clearances measured for an operation of the vane fan is shown in Fig. 9. For this particular test run the probe was installed so its polarity was aligned perpendicular to the length of the blade tips. The data was acquired at a fixed sampling rate of 400 KHZ over an 8-minute period of the fan operating at a steady state condition of 1200 RPM. The average blade tip clearance for the 16 blades over this time period was 2.84 mm. The minimum clearance detected over this period was 2.17 mm with average minimum running at 2.55 mm. These measurements were consistent with the expected operation of the vane fan and are in line with the clearance measurements that were made statically. For comparison, the measurements that were made statically at this probe's location yielded a 16-blade average tip clearance of 3.33 mm and a minimum blade tip clearance of 2.87 mm. The approximate half a millimeter difference between the static and running clearance measurements was due to blades locking in their seats during fan operation. This effect is hard to duplicate when making static measurements. Other test runs were accomplished by varying the probe's polarity (parallel to the blade tips) and acquiring data using different acquisition modes (fixed sample rate vs. synchronous sample rate). The results of these runs were similar in magnitude to the results shown below. However, it was observed that for the fan's "thick" blades, a cleaner, less noisy signal was obtained with the probes polarity aligned in perpendicular to the length of the blade tip.

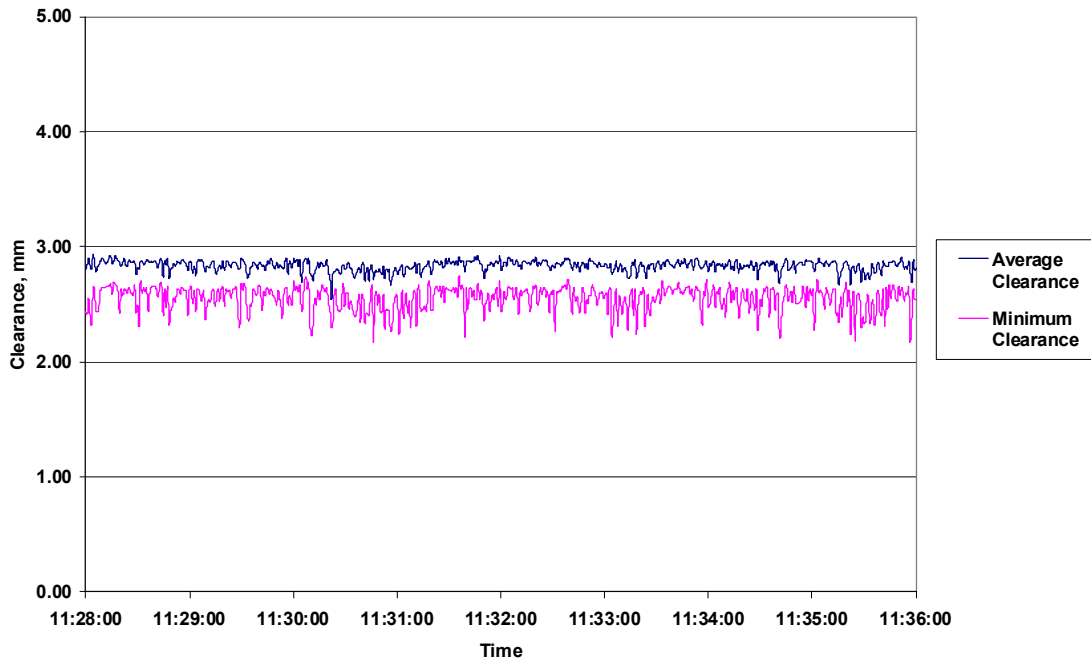


Figure 9. Average and minimum clearance time history for axial vane fan operation.

In regards to the sensors' ability to detect individual blade clearances, Fig. 10 shows the individual clearances that were measured for one revolution of the fan. The x-axis displays the blade number and the y-axis displays the measured tip clearances in millimeters. For this particular revolution the measured clearances ranged from 2.34 to 3.37 mm, with the variation in clearances between blades being on the order of tenths of millimeters. As previously indicated these clearances are in-line with the expected operation of the vane fan.

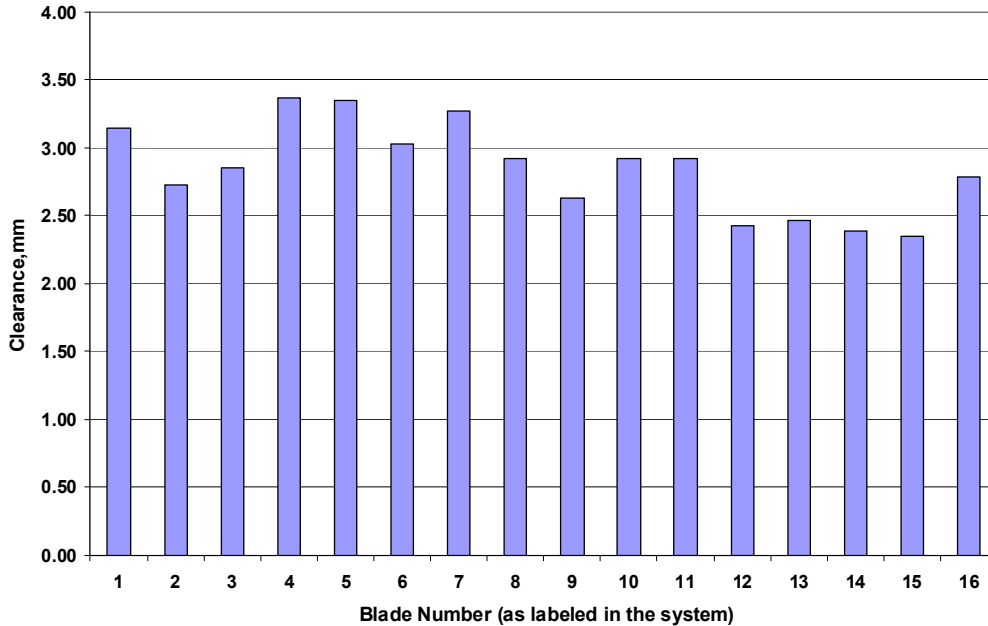


Figure 10. Individual blade clearances on axial vane fan for one revolution.

This experiment represented the first time that the microwave tip clearance probes were used at the NASA Glenn Research Center to acquire tip clearance data on actual rotating machinery. While this experiment was more of a qualitative study, its baseline objectives were successfully accomplished. Experience was gained on using the microwave probes and the system was successful in acquiring tip clearance data on the axial vane fan. In addition, the calibrations that were accomplished in the laboratory on the simulated geometry transferred well into actual use in the field. One limitation of the experiment was that a reference sensor was not installed and used to compare the readings acquired from the microwave sensors. This weakness was acknowledged and there are future plans to install the microwave sensors in this axial vane fan or another test rig along with another type of clearance sensor (capacitive, eddy current, etc.) as a means of acquiring comparison data.

V. NASA Turbofan Experiment

The third experiment was to use the microwave sensors to obtain tip clearance and timing data on a NASA turbofan test article that was tested in the Glenn Research Center's 9- by 15-Foot Low-Speed Wind Tunnel (9×15 LSWT) Facility⁸. The purpose of this experiment was



Figure 11. NASA Turbofan.

to evaluate the sensor's ability to acquire data on aero engine size test article and blades. The turbofan has 18 blades and is shown in Fig. 11. It is being used to develop and evaluate noise reduction concepts under NASA's Subsonic Fixed Wing Program. Two probes were installed 90 degrees apart in the turbofan's casing at the midchord position of the blades. The first probe was installed at the 90 degree position, which is on the left-hand side of the casing looking downstream at the fan. The second probe was installed at the 180 degree position, which is on the bottom of the casing looking downstream at the fan.

This application was a little different than the Axial Vane Fan Experiment presented in the previous section of this paper. First, the blades were made out of a non-ferrous composite material. The tips of these blades were nickel coated to allow measurement by the microwave sensors. Second, the turbofan's casing

was lined with a non-ferrous abradable material so the fan blades would not be damaged in the event of a blade rub during operation. However, for the sensors to work properly they needed to be installed in a metallic casing to allow the microwave field to properly propagate from it. To accomplish this, the sensors were recessed in the non-ferrous rub strip at a distance greater than normally done, in order to use the metallic part of the casing as the required reference plane. This also had the benefit of moving the sensors back to a much safer location in the event that a deep blade rub was experienced. For this experiment, holes were drilled all the way through the casing including the non-ferrous liner in order to facilitate the probe installation and the collection of physical distance measurements. However, in hind sight, since the sensors have the ability to see through a non-ferrous material, a better idea would have been to only drill far enough to let the probes be installed in the metallic part of the liner and to leave the non-ferrous rub strip intact. This would have resulted in a clean and intact flow path, allowing clearance measurements to be made during all phases of the test program. It is planned to pursue this type of installation for the next test entry of the NASA turbofan.

In order to make the tip clearance measurements on the turbofan a series of calibrations were carried out to map the actual clearance to the uncorrected clearance measured by the sensor. The calibration was done using the previously described calibration rig with an actual blade and the probes installed in a section of the fan casing. This setup allowed the calibration to be done in a configuration that was as close as possible to the actual use on the turbofan. It also allowed the offset due to the probe being recessed in the non-ferrous rub strip to be included in the calibration. For this application the sensor's polarity was aligned to be parallel with the length of the blade tip to maximize the amount of energy reflected from the blade. The calibrations were accomplished over a range from 1.0 to 3.0 mm between the tip of the blade and the fan casing. The calibration curve for one of the probes is shown in Fig. 12. The y-axis is the "measured" or uncorrected clearance reading that was acquired from the probe. The x-axis is the actual clearance distance between the fan casing and the tip of the blade. The resulting curve is a second-order polynomial and shows good sensitivity over the range of calibration. One issue involved with the calibration is that the clearances on the turbofan were expected to be a little under a millimeter. Due to the particular geometry of this setup obtaining a repeatable calibration of distances under a millimeter between the fan casing and blade was not possible. However, since the probes had a second-order response in the targeted calibration range, it was determined that accurate results could be obtained in projecting the curve fit for clearances that were a little under the calibrated range. This assumption held true in previous calibrations. As a means of evaluating the calibration and its repeatability, a verification test was conducted by resetting the probe and repeating the measurements across

the entire range with the clearance correction curve being applied to the measurements. The largest difference that was observed between the actual clearance and the corrected clearance in this verification was ~0.05 mm. This was a major improvement when compared to the errors observed in previous calibrations.

It needs to be acknowledged that these calibrations were accomplished after the probes were used on the turbofan. This was done because the calibrations accomplished prior to the test entry were not done with the same probe alignment and system settings that were used when acquiring data from the turbofan. In addition, prior to testing, it was noticed that one of the probes was not providing a strong signal and was replaced with a spare probe that had not been calibrated for this application. The clearance data acquired from the turbofan was reprocessed using the correction curves generated during the post calibration. Normally, a pre-test calibration is sufficient if the settings and geometry used in the calibration are consistent with the actual use on the fan or engine.

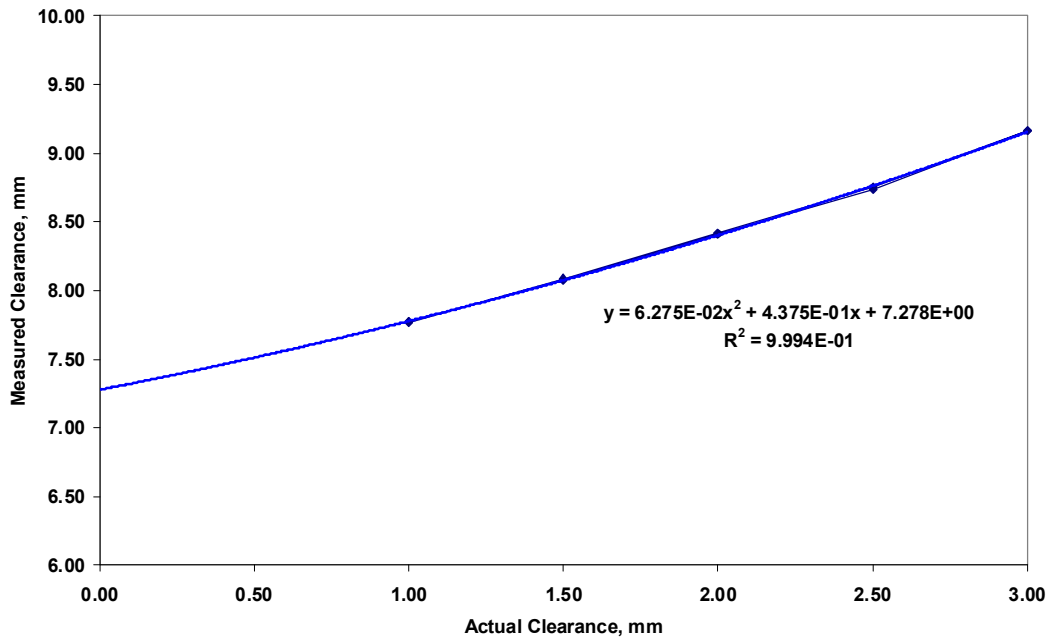


Figure 12. Calibration curve for nickel tipped composite blade.

Blade tip clearance and tip timing data was acquired for several test runs of the NASA turbofan. Data was acquired at a variable sampling rate that was synchronized to the fans speed. Each measurement consisted of two revolutions of data with 10,000 samples taken per revolution. Good clearance data was acquired in this experiment. Figure 13 shows the 18-blade average tip clearance measurements and the fan speed for one of the test runs. From these charts it is observed that the average tip clearance decreases as the fan speed is increased. This result is expected and is mostly due to the growth of the composite blades as the fan operates at higher speeds. Probe #1 measured a decrease of 0.22 mm and probe #2 measured a decrease of 0.06 mm as the speed increased to 8875 RPM. The change in clearance observed in this experiment was within the range predicted for these blades. In addition, the change in tip clearances measured by the microwave sensors were very similar to previously observed values. In a previous test entry using capacitive clearance sensors, changes in tip clearances up to 0.22 mm were observed when the turbofan was operated over the same speed range.

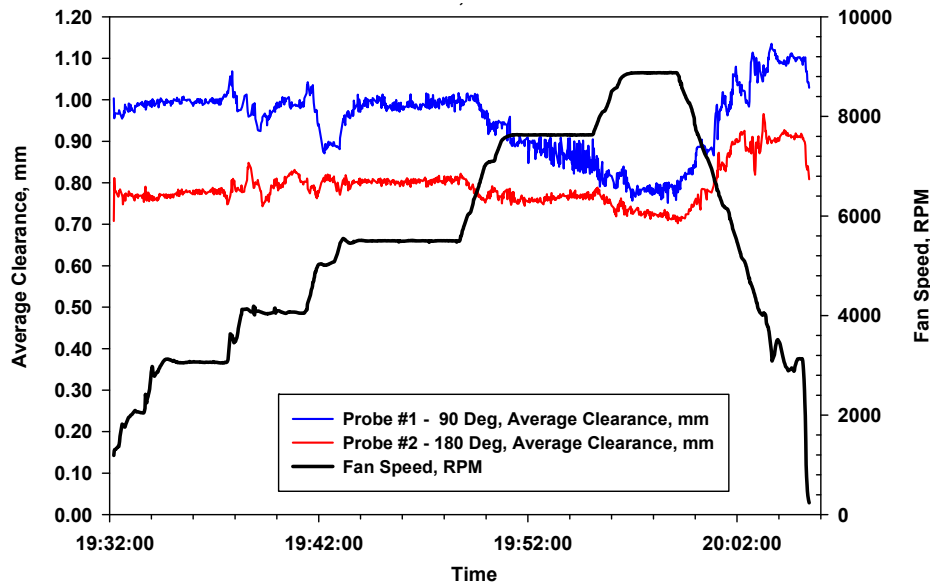


Figure 13. Average Blade Tip Clearances and Fan Speed from the NASA Turbofan Experiment.

An additional means of viewing the data is shown in the polar plots of Figs. 14 and 15. These plots show the individual blade clearances measured by each of the probes for several fan speeds. As noted previously, these plots show that the individual blade tip clearances decrease as the fan speed is increased. A more noticeable change in the individual clearances can be observed in the polar plot in Fig. 14 for probe #1. This clearly shows the decrease in the individual blade tip clearances as the fan is operated at higher speeds. A less noticeable change is observed in the polar plot in Fig. 15 for probe #2. It still shows the overall trend of the tip clearance decreasing as speed is increased, but it is just not at the same magnitude as observed by the first probe. In reality, the small change in displacement observed by the probe at this location during the run is approaching the measurable limit for using this size of probe on this blade. However, even with this observation, these plots do show that the microwave clearance probes are sensitive enough and have sufficient resolution to pick up the minor variations that exist in the individual blade tip clearances.

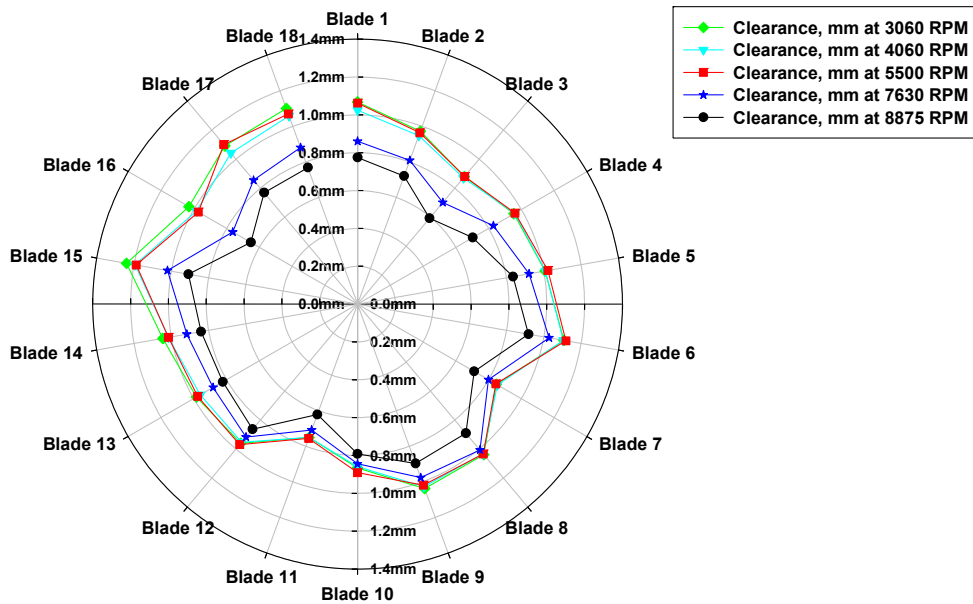


Figure 14. Individual Blade Tip Clearances for Probe #1, 90 deg location – NASA Turbofan Experiment.

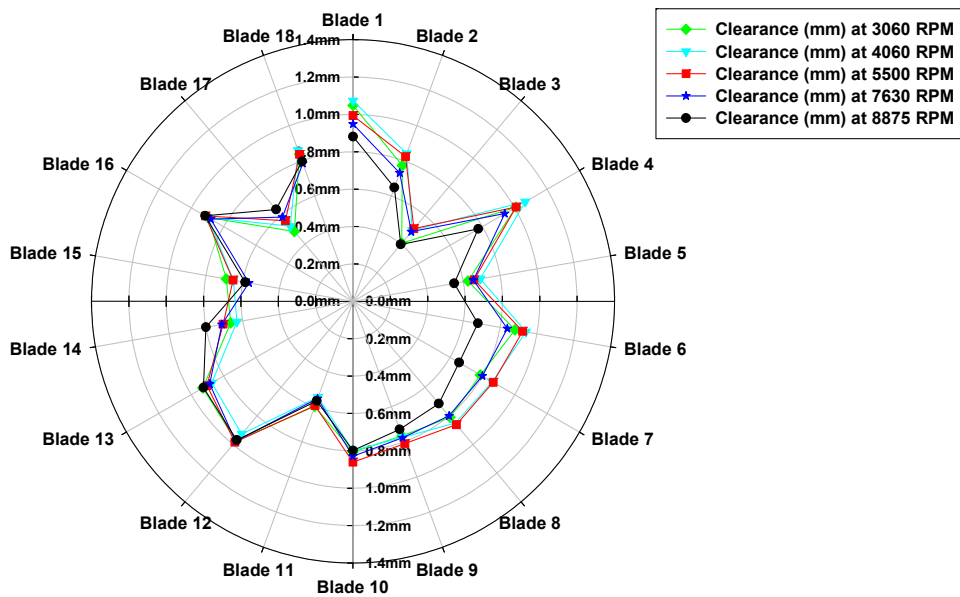


Figure 15. Individual Blade Tip Clearances for Probe #2, 180 deg location – NASA Turbofan Experiment.

One anomaly that was observed in the data of Fig. 13 is the difference in the absolute clearance values measured by each of the probes. The average blade tip clearance measurement made at static conditions for probes #1 and #2 was 0.86 and 0.91 mm, respectively. Assuming that the blades do not experience much growth at low speed, the clearances measured at these speeds should be close to the values measured statically. Using this assumption, it is observed in Fig. 13 that probe #1 was reading ~0.14 mm high and probe #2 was reading ~0.13 mm low in absolute clearance values. It is believed that this zero shift in measured clearances is due to dissimilarities between the probes' installation on the turbofan and the installation used for the calibration. Any differences in probe alignment and installation depth will affect the accuracy of the measurement. Improved methods will be used in future experiments to better control these parameters so the installation used in the calibration more closely matches the installation used on the test article. It should be noted that the tip timing data acquired in this experiment is still being processed and evaluated. It is planned to present this data in future reports.

In summary, this experiment has successfully demonstrated the microwave clearance probe's ability to make measurements on aero engine size hardware. The blade tip clearances measured by the probes were consistent with results previously observed for this turbofan. The experiment also showed that the probes can be used to make measurements on an application that is not typical for their designed use. The sensors were able to make measurements on blades made of composite materials by coating the blade tips with nickel. In addition, the sensor's ability to see through the non-ferrous portion of the rub strip allowed it to be recessed further in the fan's casing than would have normally been done. This has a positive ramification for future experiments where it will be attempted to keep the non-ferrous portion of the rub strip intact allowing these sensors to make tip clearance measurements on this fan over its entire range of testing without affecting the fan's acoustic or aero performance. It is also planned to make improvements to the calibration and installation processes so the installation used in the calibration more closely matches the actual use on an engine or test article.

VI. Conclusion

The series of experiments undertaken over the last year have demonstrated the microwave tip clearance sensor's ability to make reliable tip clearance measurements. The microwave probes were successfully used to acquire tip clearance data on an axial vane fan and a turbofan. In addition, a calibration rig was set up and the microwave probes were evaluated against several different blade geometries. Further work will be done to improve the techniques used to calibrate and install the probes so critical parameters such as installation depth and alignment can be more closely controlled in order to maximize the accuracy of the measurements. In summary, testing to date has been successful and has shown that this technology is viable in making blade tip clearance and timing measurements. More testing will be undertaken in 2009 to further evaluate the microwave tip clearance sensor's capabilities. The ultimate goal of the project is to use the microwave probes on an actual aero engine in a high temperature environment. This is being planned for the 2009–2010 time period.

Acknowledgments

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