METROLOGY CONSIDERATIONS FOR CALIBRATING TURBINE TIP CLEARANCE SENSORS

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ABSTRACT

The pressure to gain additional efficiencies out of gas turbine engines has generated strong interest in closed loop active clearance control technologies. The critical piece of information necessary for closed loop control is an accurate measure of the tip clearance. Desired system accuracies for closed loop clearance control are quite demanding for a room temperature sensor, let alone one that is required to operate within gas paths of 2000°C and higher. Since there is no ground truth in an engine test to determine the actual clearance, special care must be taken during the calibration and evaluation of tip clearance sensor in the laboratory to determine that engine conditions are simulated accurately. Current state of the art sensors, such as microwave tip clearance sensors, able to survive in these environments typically have measuring spot sizes larger than the features on the blades, introducing spatial filtering to the sensor output. Other items that must be considered include axial shifts, as well as the blade geometry after tip grinding. In order to guarantee accurate results, laboratory test systems should use the actual tip geometry and move the blade in the same angular position in order to minimize abbe offset errors. In this paper, these items are discussed within the context of a microwave tip clearance sensor.

INTRODUCTION

To date, measuring tip clearance within gas turbine engines has been confined to providing information back to engine designers. Tip clearances should be designed to run as small as possible, yet still not rub the case as the engine goes through its operating envelope. For aerospace engines, tip clearance pinch points occur on takeoff and landings as differences in thermal expansions between the case and rotor occur during the full output power condition at takeoff as well as the thermal soak back that occurs immediately after landing.[i] Similar conditions exist for power turbines on engine startup and shutdown.

Large tip clearances can have a substantial impact on efficiencies. It has been reported in the literature that a 0.001” the tip clearance can be closed can contribute as much as an additional 0.1% in efficiency improvement.[ii] Normal operation of the engine typically causes clearances to increase over time as the blades and case coatings gradually erode due to the gas path or mechanical contact between the blades and case. Active clearance control systems are gaining more interested because they could be designed able to adjust the tip clearances dynamically for the current engine condition. In this manner, clearances could be optimized for the current location within the operating envelope as well as assist in maintaining constant engine performance in-between overhauls.

To date, the main types of sensors that are used for measuring tip clearance include capacitive, eddy current, optical, and microwave. All of the measuring techniques except for optical can be thought of as “large spot size” sensors. These sensors have measuring patterns that are larger than the features on the blade to be measured. From a metrology and measurement perspective, this presents some unique challenges in obtaining accurate measurements.

For power systems turbines, clearances often run between 2-8 mm. For aerospace turbines, running clearances of 3 mm and less are common depending on which part of the engine is being measured. Measurement sensitivities of 0.025 mm or less and accuracies of 1 to 3% are desired.

Verifying Sensor Accuracy

One of the biggest challenges with tip clearance measurement is demonstrating accuracy within an actual engine. For large spot size sensors and sensors that relate differing physical parameters to distance such as capacitance and eddy currents, the sensors must undergo a calibration. It is difficult and costly to accurately represent the engine environment in the laboratory. Therefore, approximations are often made to simplify the calibration. This can range from the surrounding geometry in which the probe is mounted to the radius at which the calibration geometry is moved by the probe.

Another big factor to consider is the temperature changes that happen inside real engines. As the temperature changes, everything being measured will dimensionally change due to the material’s coefficient of thermal expansion. Therefore, it becomes nearly impossible within a laboratory environment to heat a test setup to typical engine temperatures of and guarantee the actual clearance used to verify accuracy.

Since it is nearly impossible to verify what the running clearances are in the actual engine there is little feedback to determine if the measurement is accurate. In addition, models of tip clearance running conditions have been developed, however, often these models have been adjusted to fit the behavior of the sensors and not vice-versa. Therefore, there may be a false sense of confidence when the models and measurements agree.

Therefore, a more rigorous approach needs to be developed in calibrating and verifying the sensor accuracy that better models the engine in which the sensor is installed. The purpose of this paper is to identify certain engine parameters that have a significant impact on sensor accuracy to make sure that they are probably handled within a laboratory setup.

Microwave Sensor Description

For the results in this paper, a microwave probe was used that consists of a continuous wave (CW) microwave signal which allows motion of the blade to phase modulate the return signal. A phase measurement from the return signal is processed to determine the distance to the blade. The phase is related to distance by knowing the transmit frequency of the microwave signal. Two versions of the system are currently used, a 6 GHz system for power systems and a 24 GHz system for aerospace applications. The differing frequencies are used to

The measurement signal chain consists of an electronics module containing all of the microwave circuitry and digital signal processing connected to a probe via a high temperature microwave cable. A schematic representation of the system is shown in Figure 1. The cable is typically a microwave-based mineral insulated cable capable of withstanding temperatures up to 900°C and the probe is constructed out of high temperature metals and ceramic dielectric materials.

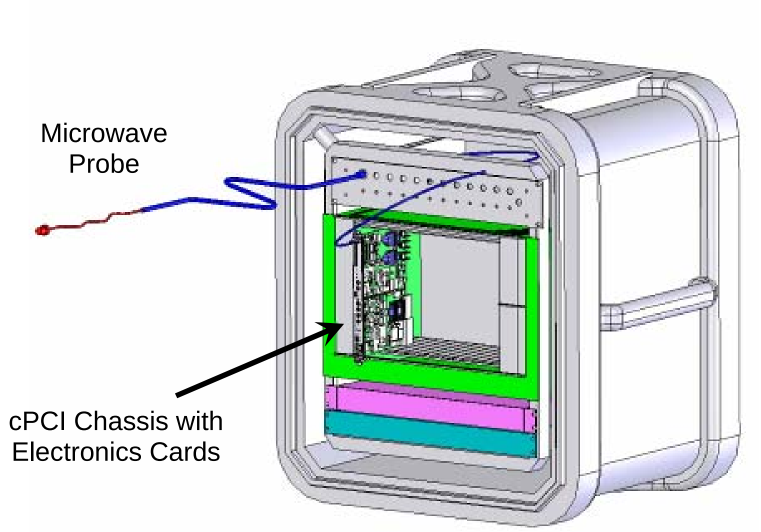

Figure 1. Representation of microwave tip clearance system

SPATIAL FILTERING

An important metrology consideration in making turbine tip clearance measurements is the concept of spatial filtering. Spatial filtering is important to understand for any measurement system whose field of measurement, also referred to in this paper as spot-size, is on the order of or bigger than the object or feature that is being measured. Spatial filtering describes the process by which a physical measurement over some spatial area is filtered down to a single numeric measurement. Spatial filtering affects almost all dimensional measurement systems to some extent. Take, for example, the extremely basic measurement of a pair of calipers. Calipers have two surfaces used for measuring a physical object. The surfaces may touch the object at one or many places, yet the measurement is reduced to a single numeric value. In this case, the result of the spatial filter is the maximum width of the object along the axis of measurement—taking into account the whole object between the two measurement surfaces.

Spatial filtering affects both contact and non-contact dimensional measurements although the mechanism is not quiet the same. With contact measurements, such as the caliper example or a commercial CMM, the effect of spatial filtering is defined by the physical size of the measurement surface or probe. Commercial CMMs usually have a spherical tip at the end of the measurement probe. The CMM detects that the spherical tip has made contact with the surface of the object, but it does not differentiate between touches at different points on the tip. **Figure 2** illustrates this phenomenon.

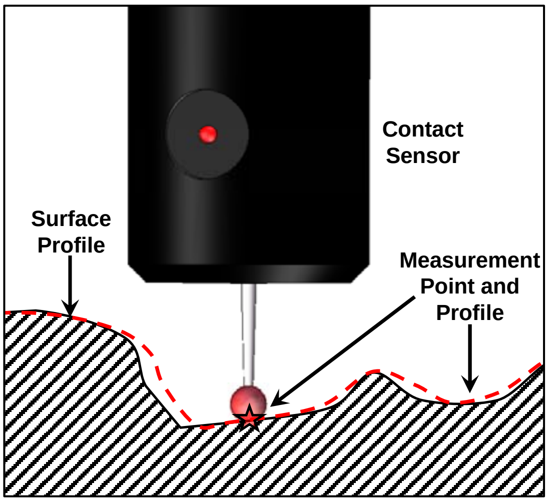

Figure 2. Illustration showing ruby-tipped touch probe and the resulting spatial filtering of contact measurements

More information about the angle of the touch must be added in order to improve accuracy lost in spatial filtering. Even with added information, a CMM will not be able to accurately measure a surface feature that is smaller than the probe tip.

In non-contact measurements, the effect of spatial filtering is slightly more complex. All non-contact measurement systems have some effective field-of-view. Outside this field-of-view, the sensor is negligibly affected, but everything inside this field-of-view has some effect on the measurement. In the end, the measurement is some aggregate of the measurement of everything within the sensor field-of-view, as illustrated by **Figure 3**. This may be thought of as a weighted average of individual measurements from every location in the field-of-view.

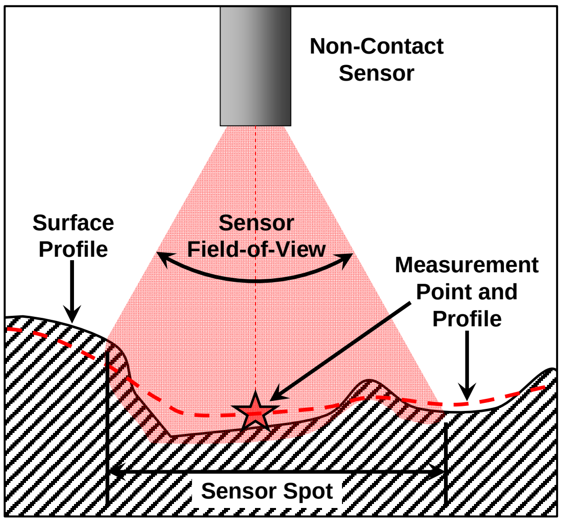

Figure 3. Illustration showing spatial filtering effect on non-contact measurements

For non-contact measurement systems, spatial filtering presents an additional difficulty in that it is affected by distance and any features on the blade tip. Many non-contact sensors have a spot size that gets larger with increasing distance. As the target moves further away from the sensor, more of the target is visible to the sensor, and a larger region of the blade contributes to the overall measurement. The end result is basically more severe blurring as a function of distance. In addition, any features that suddenly become visible to the sensor will further complicate the measurement. **Figure 4** shows this effect; the blade is increasingly blurred as clearance is increased.

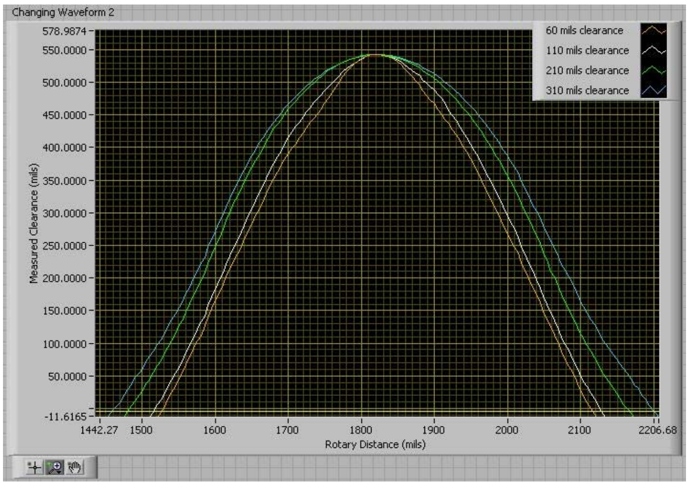

Figure 4. Measurement of a simplified blade at several clearances showing the blurring effect of spatial filtering.

For tip-clearance measurements, spatial filtering significantly affects almost all of the systems in use today. The amount of spatial filtering is defined by the spot-size or the size of the fields used for measurement. Microwave sensors, eddy current sensors, and capacitive sensors all have fairly large spot-sizes relative to the size of the blades being measured. Only laser systems have a very small spot-size. However, for the hotter areas of the engine optical probes have proven unrealizable. In order for spatial filtering to become insignificant, the spot-size must be much smaller than the smallest features to be measured on the blade. In most cases the smallest feature is the squealer tip.

The effect of spatial filtering is defined by the geometry of the sensor's spot and the geometry of the blade. The result can be modeled as the convolution of the two geometries separated by a certain distance (clearance). The exact solution to spatial filtering would be to invert the convolution for each blade that passes by; however, the complexity of the geometry involved makes this task difficult. But since the geometry of the sensor spot and blade tip remain relatively constant, the solution may be empirically derived as a function of clearance to form a calibration curve, matching the output of the sensor to a known actual clearance. Indeed, this is the method used by all large spot size tip clearance systems today. Extreme care must be taken in creating this calibration curve to consider all of the possible sources of error to ensure that this calibration will hold fine accuracy when applied to actual engine measurements. Any differences between the calibration and the actual engine should not be overlooked because a number of small differences may add together to result in significant error. The major factors defining the geometry of the measurement are the motion profile of the blade, the blade tip geometry, and the casing geometry immediately surrounding the probe. An in-depth review of tip clearance measurement geometry follows in order to adequately consider all of the factors affecting this calibration and measurement.

TIP CLEARANCE MEASUREMENT GEOMETRY

In tip clearance measurements, because of the significant size of the spot of most sensors compared to the size of the blade features being measured, spatial filtering has a dominant effect on measurements. Spatial filtering is a geometric effect, so a detailed understanding of the actual geometry in a turbine and how it changes during operation is important. The following sections focus on how turbine motion affects tip clearance measurements and then takes a detailed look at the important aspects of the tip geometry of a turbine blade.

Engine Dynamics and Tip Clearance Measurements

The most obvious motion of a turbine is the rotation of the disks; however, it is insightful to analyze how this affects tip clearance measurements. Spatial filtering is an effect based purely on dimensional geometry and so there is no change in spatial filtering due to changes in speed. Speed will only affect measurements if the specific sensor has some response time that is significant relative to the speed of the turbine. In the example of Vibro-Meter's microwave tip clearance sensor, the response time is defined by the speed of microwave transmission which is very close to the speed of light. Therefore, there is no effect of speed on the sensors' measurements.

But the fact that the turbine is spinning adds additional complexity to how tip clearance measurements are made because it becomes impractical to take measurements only precisely when the blade tip (or even more particularly, the closest point of the blade to the case) is directly in front of the sensor. This makes choosing the exact point in time at which to take the measurement difficult. What the sensors measure is a signal of a blade starting to move into the field of view on an arc and then past the sensor. This provides a time series of measurements as the blade passes by. Additionally, any speed dependence of sampling, processing, filtering, or averaging must be directly tied to the engine speed for accurate measurements.

Mechanical growth of turbine components is a further source of motion in a turbine engine. This growth is normally related to either centrifugal force or temperature. Both blades and disks grow as a function of centrifugal force, which is directly related to speed and radius. In addition, the blades, disks, and case will grow or shrink with temperature changes. These are the main sources of pure tip clearance changes. From a measurement perspective, this is the major motivations behind the measure of tip clearances. In a simple way, these growths are all directly out from the center-line of the turbine and result in pure changes in tip clearance. However, in reality, the situation is much more complex and results in other changes such as casing out-of-roundness and axial growth.

Casing out-of-roundness is the result of asymmetric forces on the case of the turbine due to unequal heating, asymmetry in the mechanical design, and outside loading. The casing geometry, of course, directly affects the tip clearances around the turbine. The main effect of casing out-of-roundness on tip clearance measurements is more of a systems difficulty because it means that a measurement from one point around the case is not necessarily the same as the measurement at another point. The measurement at any one point around the turbine is not significantly affected by case distortion—it is merely a seen as a simple clearance change.

The same effect is seen by disk eccentricity. Disk eccentricity is when the center-line of the rotating shaft and disk is not perfectly aligned with the center-line of the case because of freedom of motion in bearings or very slight shaft bending. The result is increased tip clearances on one side of the turbine and decreased tip clearances on the other side as the rotor moves from one side to the other. There is no additional affect on tip clearance measurement geometry.

A final, and very important, motion in turbine operation which affects tip clearance measurement geometry is that of axial shifts. Axial shifts are motions of the entire disk and blades forward and back axially during turbine operation caused by loading and thermal growth of the rotor. The axial motion can be over 10 mm in a power systems turbine. This axial motion is a more complex motion caused by differential heating as well as turbine loading and speed. For tip clearance measurements, axial motion is a very significant issue. When the axial position changes in a turbine, the geometry of the blade in the sensor's field of view may also change significantly, which directly affects the measurement. **Figure 5** shows how axial shift may change the profile that the sensor is looking at as the turbine rotates.

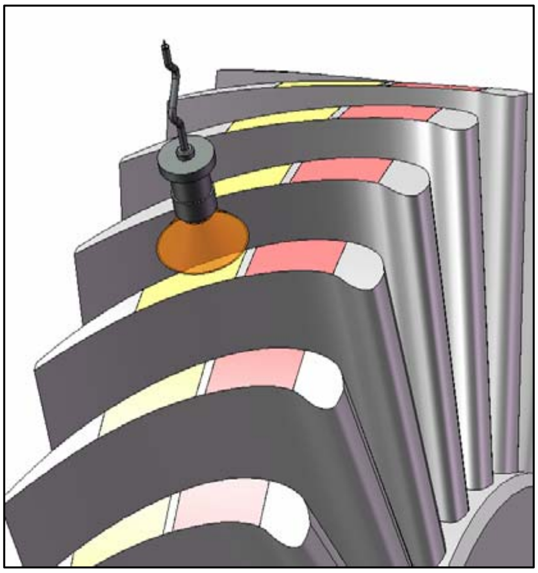

Figure 5. An illustration showing axial motion shift.

Because spatial filtering is directly dependent on the geometry within the field of view of the sensor, viewing a different portion of the blade may change the measurement. The amount of change will be dependent on the amount of geometry change as a function of axial position as well as the particular spatial filtering properties and spot-size properties of the sensor.

Blade Tip Geometry and Tip Clearance Measurements

The features in the tip of the blade are themselves often significantly larger than this. As a result of spatial filtering, a measurement may not be made off of only one surface at a time—the measurement is inherently an aggregate off of a larger surface. Therefore, it is important to look in detail at all of the features of the blade tip since they will all have some influence on the tip clearance measurement. It is especially important to understand how these features may vary between blades and how they will change throughout turbine operation. Additionally, these features will play a significant role in calibration and thus must be considered.

The most prominent feature of most blades tips besides the overall shape of the airfoil is the squealer tip. Blades may have a squealer tip along the pressure and suction sides of the blade or just on one side. The squealer plays an important role in the measurement of the blade tip. The desired measurement off of the blade is the distance to the highest point along the squealer tip, since this defines the overall clearance between the case and the blade tip. This is the case, even if the squealer tip is much thinner than the entire blade. Because of spatial filtering, a significant portion of the measurement may be the result of the platform since it is the larger surface. The effect of spatial filtering due to the squealer tips is defined by the ratio of the width of the squealer to the platform as well as the height difference between the squealer and the platform. This is important in actual turbine operation in two ways. First, there is some tolerance on the height of the squealers. This is a small factor, but it should be considered as it contributes to the overall uncertainty of the measurement. Secondly, and more importantly, the squealer tip geometry changes as a function of axial position. As the disk of blades moves axially in front of the sensor, the squealer tips may change both the ratio between the width of the squealers and the platform as well as the height difference between the squealer and the platform. Both of these aspects will affect the overall spatial filtering and hence the final measurement of the blade tip.

Of course, some blades are shrouded and have no squealer tips, but in this case, there are often additional features which affect the measurement in the same way—especially as a function of axial position. Features such as cooling passages, seals, slits between blades and other design features are all important to tip clearance measurements and should be considered. A feature which only comes into the sensor's field-of-view dependent upon the axial shift may cause errors in clearance measurements. In this case, the addition of another feature to the spatial filtering scheme of the sensor may significantly change measurements while giving no other indication that something is incorrect. However, to date, the authors' analysis has dealt with only un-shrouded blades.

Manufacturing tolerance is another aspect of blade tip geometry that must be considered in measuring blade tips. The tolerance of the squealer tip width and height may be on the same order as the accuracy desired, which will then be difficult to achieve. Small surface features and imperfections may also affect the measurement of a blade slightly.

The final step in manufacture of blades is often a tipping step in which blades are spun in a disk while the tips are ground to the final dimension to match the radius of the case. Also, this process removes slight differences between the blades by machining them all at once in the same way. However, this process is limited by the seating tolerances of the individual blades. In tipping, the blades are generally spun fast enough to adequately seat the blades as they would in engine operation, but very small changes in this seating are amplified at the blade tips. This tolerance will determine the difference in height between blade clearances during engine operation.

The rounded surface of the blade tip is an important factor to consider for tip clearance measurements because of spatial filtering. The radius at the blade tip will certainly influence how the sensor spot convolves with it to the final measurement because the radius will cause the portions of the blade not directly in front of the sensor to appear farther away, thus changing the aggregate measurement. For aerospace applications with smaller radii, this error will be significantly increased.

Therefore, it should not be assumed that a calibration geometry with a radius other than this radius or no radius at all would be a very good approximation of the measurement geometry. The best calibration would be achieved using an actual blade with tipping already performed.

Other factors such as blade untwist and blade wear should also be considered when measuring tip clearance, though presumably they will have second-order effects on measurements. Blade untwist may adversely affect blade tip measurements by changing the portion of the blade in the sensor's field-of-view and changing the blade-to-space duty cycle. Because of spatial filtering and then any other signal processing before the final measurement is derived, untwist may have a measurable affect. For example, given a 15 mm wide blade with a 40° angle-of-attack relative to the airflow direction, and untwist of just 2° would result in a 1% duty cycle change which would be significant for any sensor with a speed dependent processing scheme.

Blade wear is perhaps slightly more problematic. If blades wear due to blade tip rubs, it is likely that the squealer tips will be shortened somewhat. Shortened squealer tips mean that the spatial filtering may significantly change because the squealer tips will be at a different height relative to the platform. Also, the condition of the blade tip may affect the measurement because of sensitivities to surface quality or finish or the presence of oxidization, depending on the sensor type.

Yet another degree of freedom is added to the tip clearance measurement if the case is not cylindrical at the blade tip but conic. In a conic section, a tip clearance change may result either from growth in the blade or case or from a change in axial position.

SENSOR CALIBRATION AND LABORATORY VERIFICATION

As discussed earlier, calibration is used to overcome the effect of spatial filtering by empirically characterizing the relationship between the sensor measurement and actual clearance. All of the geometry factors considered here have a part in determining the final measurement of a tip clearance sensor. Much of the sensitivity of the sensor is removed by calibration. The other factors must be tested in order to truly determine their effect on a sensor.

Since there are so many factors playing into this measurement, calibration should be performed using actual blade tip geometry. This removes a major source of uncertainty from the measurement. Other factors are small perturbations from this baseline, but calibration using anything other than the actual geometry adds uncertainty into the baseline. Additionally, using the actual geometry of the blade tip with the exact motion of the turbine allows one to adequately characterize any deficiencies in signal processing due to averaging or filtering.

Vibro-Meter has designed and built an advanced dimensional calibration facility in order to test in extreme detail the quantitative effects of each of the previously outlined factors. The calibration facility tests sensors using actual blades moving in exactly the same motion found in the turbine. The calibration facility then has the capability to test the sensor robustness to many factors encountered in actual engine operation. The test setup consists of four fully coordinated high-precision motion axes capable of testing sensors against most all turbine geometries available (see **Figure 6**).

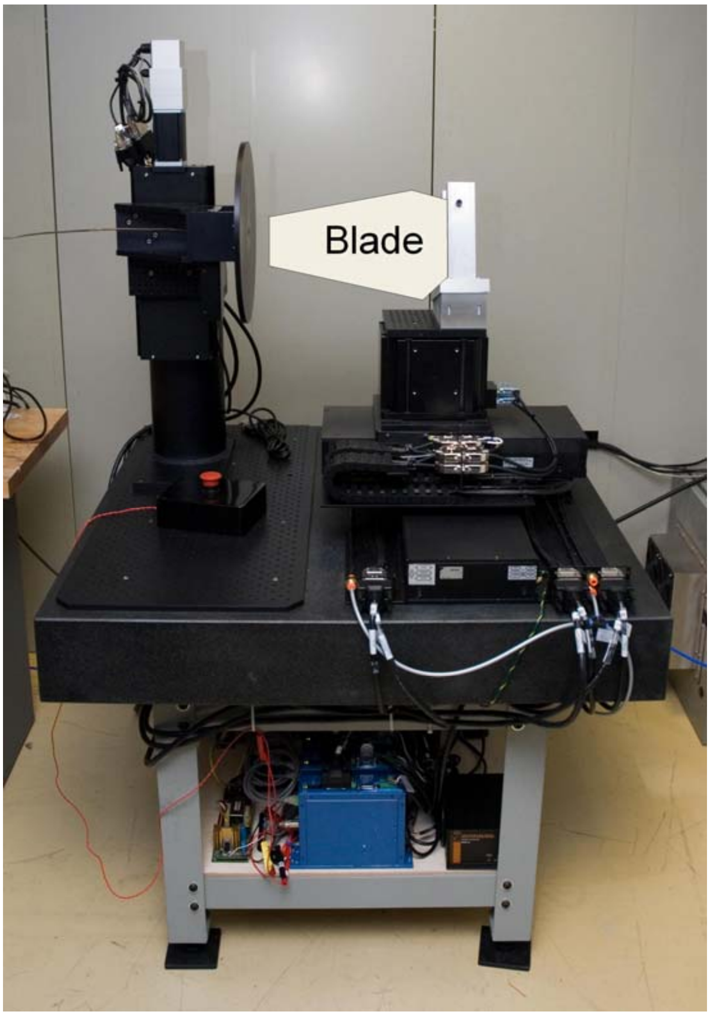

Figure 6. The test setup at Vibro-Meter's Swiss facility.

The blade is carried in front of the sensor on top of two linear axes and one rotary axis, enabling multiple blades and even small disk sections to be swept past the sensor in exactly the same motion as in turbine operation. The calibration setup may also be configured with a commercial CMM probe instead of tip clearance sensor in order to perfectly characterize the blade geometry for very fine adjustment and measurement comparison. Sensor measurements are perfectly synchronized to the blade motion and digitally stored in high definition for profile and signal processing analysis. The test setup will soon be enclosed in a temperature and humidity controlled chamber in order to ensure dimensional stability of all the parts of the test setup and validity of the measurements.

Fixturing and blade tolerances as well as motion profiling have presented themselves as challenges to obtaining a truly accurate calibration facility. However, these difficulties have been overcome by the addition of a commercial CMM probe which allows automated re-zeroing of the test setup to the actual geometry of the blade being tested. Small geometric tolerance issues in fixture design and manufacture may result in severe errors at the end of longer power-generation blades, but these errors are removed by profiling the tip of the blade using a CMM probe and using the measurements to calculate coordinate transformations to exactly correct for those errors in the motion profile. The result is precise control of the tip orientation and motion profile through more complex arc and spline motions in the stages themselves.

CONCLUSIONS

Making tip clearance measurements in a gas turbine is a difficult challenge. In order to accomplish this, it is of utmost importance that one must begin with a very detailed geometric analysis of the turbine around the area of measurement. None of the sensors that hold promise of reliably making this measurement within the hottest areas of the engine have an extremely small spot-size, so geometric complexities will certainly affect the measurement. Very close attention should be paid to geometric factors that may change during engine operation because they may influence the measurement without having any way of detecting or compensating for them. Spatial filtering in tip clearance measurements can blur features together and influence the overall measurement in small and undetectable ways that result in inaccuracies in the final measurement.

Because of spatial filtering, calibration is required for sensors with large spot sizes. Calibration can remove any effects of spatial filtering from the clearance measurement unless the measurement is confounded by other changing factors than merely clearance. Therefore, calibration must be performed as closely as possible to the actual engine installation geometry. Attention must be paid to details such as exact blade tip geometry, casing geometry and the motion profile used in calibration. All of these will potentially add error into the calibration process and hence into the installed measurements.

Vibro-Meter is in the process of finalizing the development of a very high precision calibration facility to meet all of these requirements. The test setup improves over standard tip clearance calibration techniques by using actual blades moving along the exact radius of the engine in an extremely precise and accurate way. Additionally, the calibration facility is designed to test the sensor sensitivity to other changing geometric factors that may be seen in actual installation. In doing this, this system will ensure the accuracy of its sensors to a level previously unattainable.

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