THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL ENGINEERING

Development of Laser V-Probe Calibration Methods for Measurement of Turbine Blade Tip Clearance

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SPRING 2024

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

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ABSTRACT

Gas turbine engines are often used in applications where it may be necessary to produce large amounts of power. In the turbine section of the engine, blade tip clearance is an important measurement. With too small of a clearance, operational safety can be negatively impacted. If the clearance is too large, turbine efficiency may be decreased due to a leakage vortex, which causes additional resistance for blade rotation. In the Steady Thermal Aero Research Turbine (START) Lab at Pennsylvania State University, capacitance probes are typically used to measure this clearance. Through this project, the calibration of optical V-probe sensors to measure blade tip clearance is investigated. By the manufacturer, calibration curves were created on a 24-inch diameter disk. When used on rigs with varying radii, new calibration curves must be generated: here, a 7.8” diameter disk was used. Results from this study document the creation of operating procedures for calibration purposes. The calibration data are also compared to data collected on a different disk diameter.

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ACKNOWLEDGEMENTS

I have had a great experience conducting my thesis research at Penn State's START Lab for the past few semesters. The graduate students and faculty in the lab are always willing to take the time to help me learn. I am very thankful for all the guidance and advice I have gotten in the past few years at the START Lab.

I would especially like to thank my thesis supervisor, Dr. Reid Berdanier, for all the guidance he has provided throughout this process. He gave me the opportunity to perform my research at the START Lab. Dr. Berdanier taught me not only how to approach problems with an engineering mindset, but how projects within engineering work in a professional setting. I am very grateful for the opportunity to have worked with Dr. Berdanier and for all of the lessons I have learned from him.

I would like to thank Dr. Daniel Cortes Correales for his help in forming and revising this paper. I would also like to thank the Department of Mechanical Engineering faculty who worked with the Schreyer Honors College to guide me through the process of writing this thesis.

Chapter 1 Background

1.1 Gas Turbines

Gas turbine engines are used in multiple applications to produce large amounts of power. They operate using a Brayton cycle [1]. This cycle consists of multiple steps that lead to propulsion or energy generation. First, air is pulled into a compressor, which causes an increase in pressure. The high-pressure air then moves into a combustor. Here, it is combined with a fuel, which causes an increase in both temperature and pressure. The gas then travels to the turbine. The high-pressure gas expands and causes blade rotation in this section. This flow then proceeds to the final step, which varies based on application. The turbine either powers an electrical generator or the flow exits for propulsion. Figure 1 shows a diagram of a gas turbine engine.

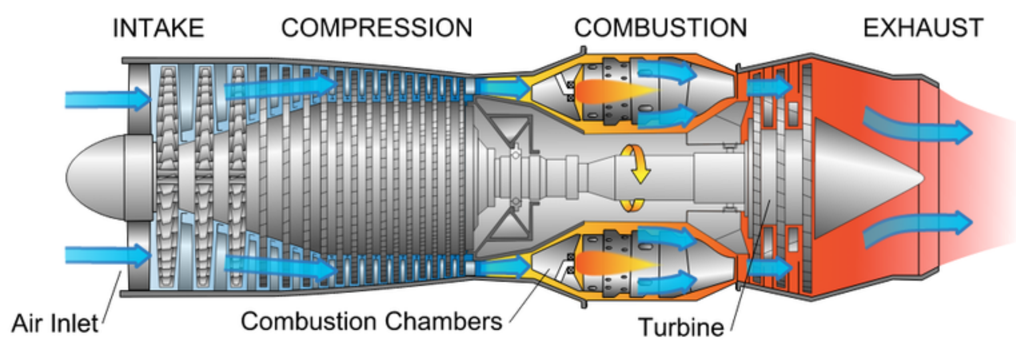

Figure 1: Diagram of a gas turbine engine [1]

To minimize environmental impacts, it is important to study the ways in which we can manufacture and maintain gas turbine engines to use less fuel. One way of doing this is to increase the efficiency of the engine. There are many factors that can impact engine efficiency, including blade tip clearance.

1.2 Penn State START Lab

The Pennsylvania State University is home to the Steady Thermal Aero Research Turbine (START) Lab. At this facility, turbine heat transfer and aerodynamics are studied. Much of the research performed targets efficient and durable turbine hardware [2]. Projects include turbine cooling, development of sensors and instrumentation, advanced additive manufacturing for turbines, and the integration of sensors through additive manufacturing. The START Lab uses a turbine test section for this research, as seen in Figure 2. The turbine hardware is in a continuous, steady-state, high pressure flow environment to simulate the environment that is typically seen within gas turbine engines [3].

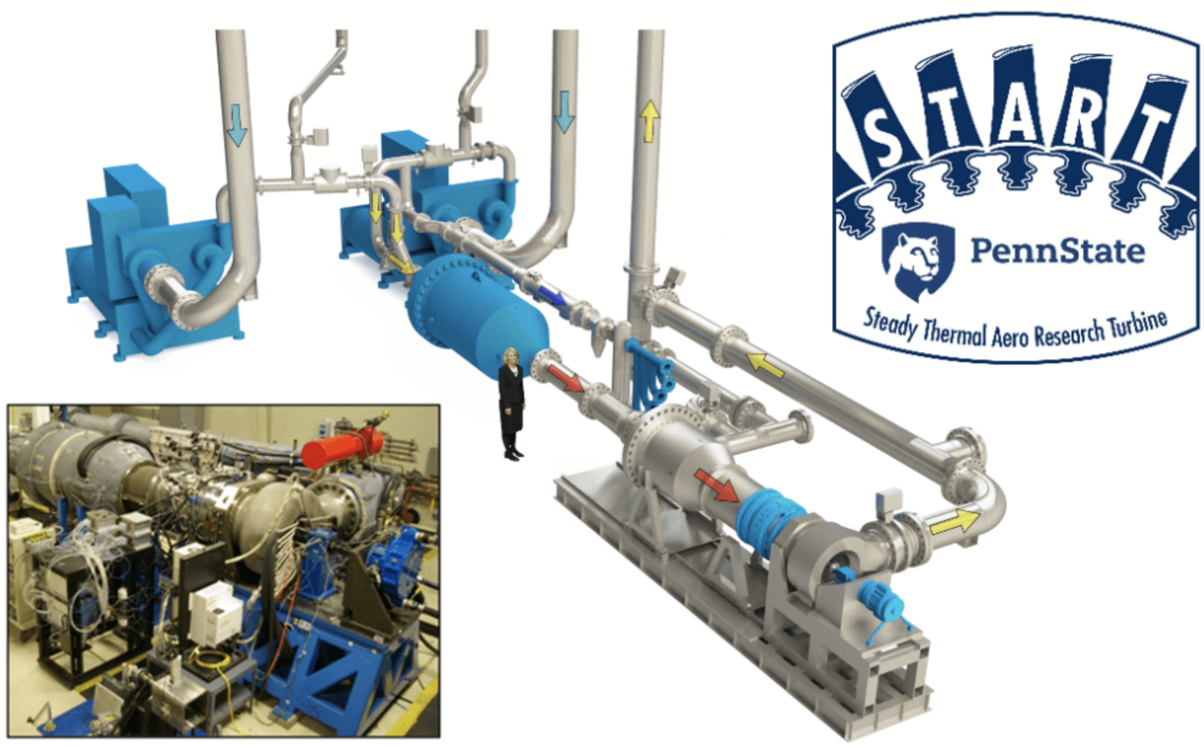

Figure 2: Test turbine at Penn State's START Lab [4]

1.3 Blade Tip Clearance

Blade tip clearance is the space between the edge of a turbine blade and the casing of the turbine. A diagram of blade tip clearance can be seen in Figure 3. Variation in this clearance can impact turbine operational safety and turbine efficiency [5].

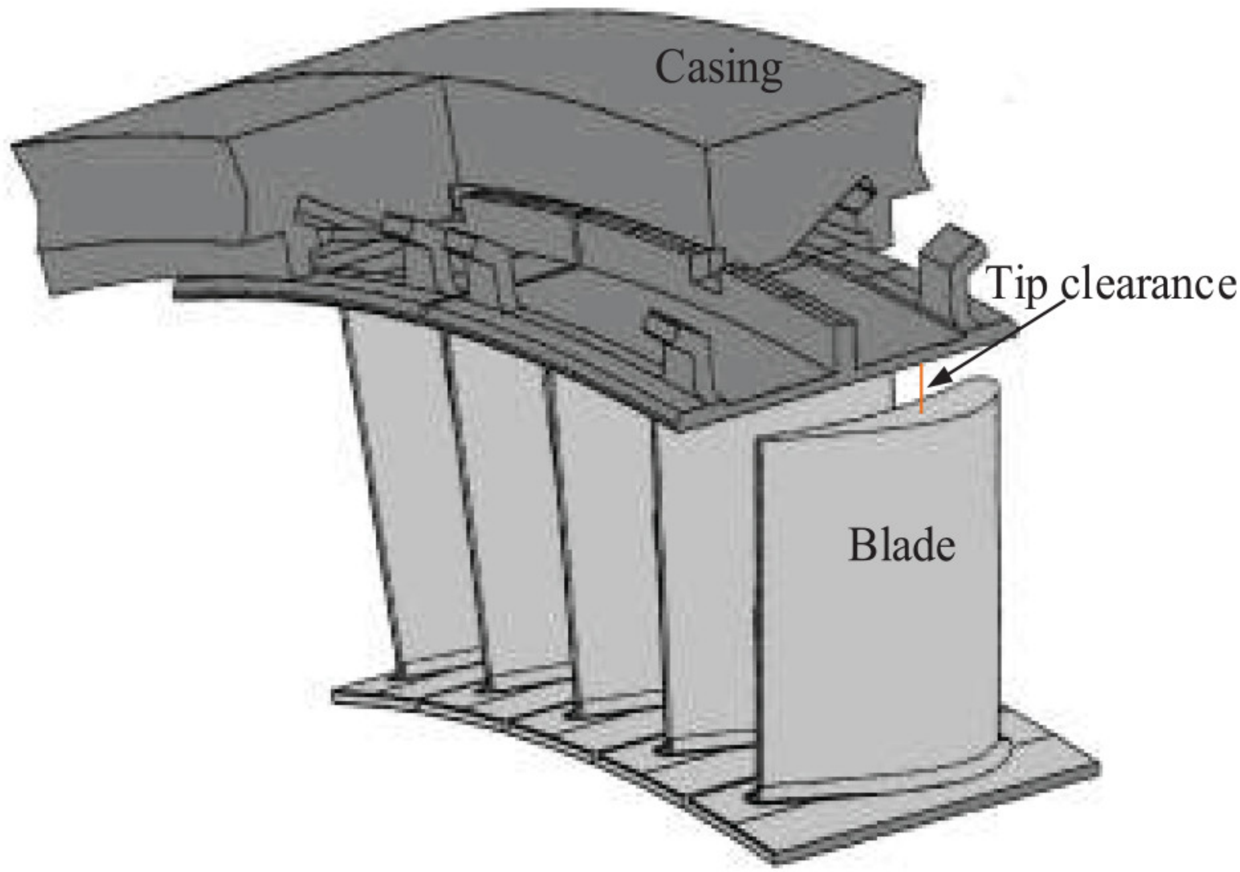

Figure 3: Diagram of blade tip clearance [5]

With an increase in tip clearance, a decrease in turbine efficiency is seen. In a modern gas turbine compressor, when tip clearance increases by 0.125 mm, it results in an efficiency reduction of 0.5%. Blade tip clearance can have an impact on the rate of fuel consumption as well [6]. With a 1% increase in blade tip clearance, fuel consumption rate increases by about 3%.

Turbine blades rotate due to the high-pressure gas that travels from the combustor to the turbine. The high-pressure gas expands, causing rotation. While blade tip clearance is necessary for operational safety, the existence of this clearance causes flow loss. This flow loss leads to a decrease in turbine efficiency, which increases the amount of fuel used. Figure 4 shows a model of flow field around the blade tip clearance. A leakage vortex is seen, which provides additional resistance in rotation of turbine blades [7]. This increases the amount of energy necessary to rotate turbine blades. To maintain this additional power, more fuel is necessary in the combustor stages of the Brayton cycle.

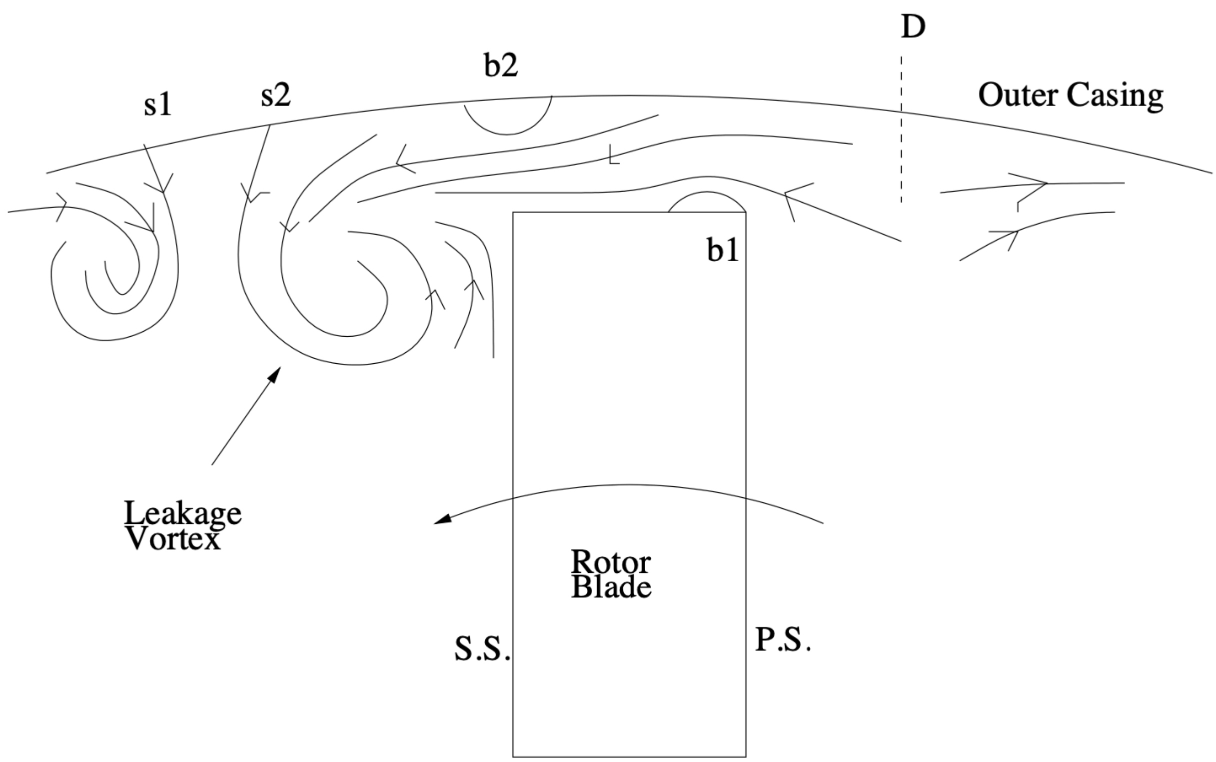

Figure 4: Model of flow field around blade tip clearance [7]

With too small of a clearance, operational safety hazards occur [8]. There is high risk if the turbine blade and casing come in contact. At the high speeds turbines tend to operate at, friction between the blades and casing may damage hardware within the engine.

1.4 Comparison of Probe Measurement Technologies

Different types of measurement probes can be used to determine the blade tip clearance within a turbine. Two of the most commonly used probes are capacitance probes and eddy current probes.

Capacitance probes are designed to work even in high temperature conditions. During rotation of the turbine blades, capacitance is measured. Capacitance probes use capacitance parallel plate theory to determine the distance between blade tip and casing. The measured capacitance is converted into a voltage measurement. A direct correlation between this voltage and the clearance can be established. These probes are designed to perform these calculations even on blades that are rotating with high speeds. Figure 5 shows the set-up of these capacitance probes.

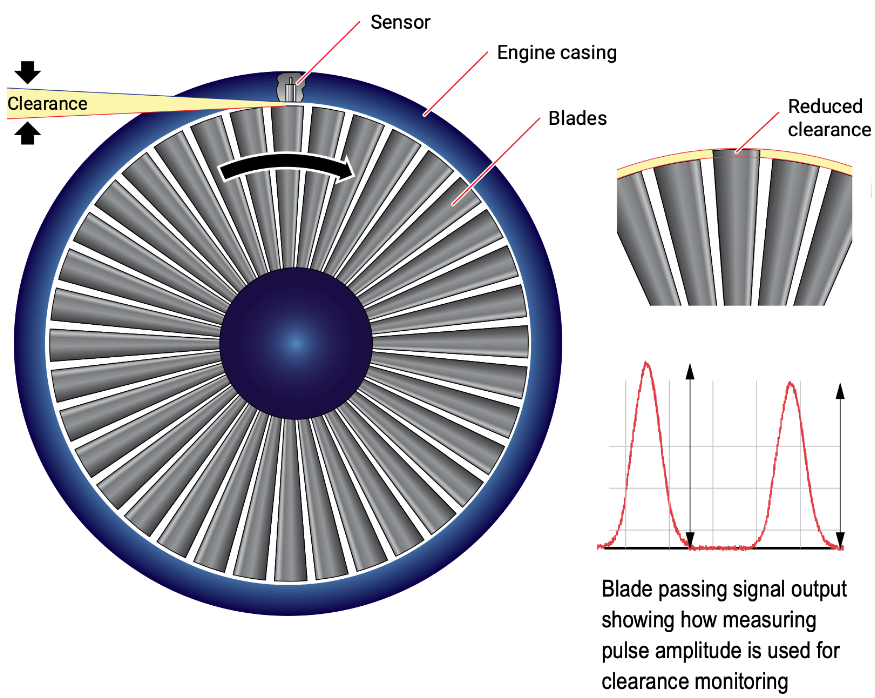

Figure 5: Set-up diagram for CapaciSense 5-series FM clearance measurement system [9]

Capacitance probes tend to have a high heat resistance [5]. They also have lower size and weight than some alternatives. For these reasons, capacitance probes have become a widely used method of measurement for blade tip clearance. However, there are some drawbacks with this method. Calibration of capacitance probes can be quite difficult, and miscalibration can lead to inaccuracy in measurements. The accuracy of the system's measurements is also sensitive to several factors, including environmental disturbances, deformation of casing or probe, and, as previously stated, calibration error.

Eddy current sensors are another commonly used method to measure blade tip clearance. Eddy current sensors use a magnetic field variation to calculate the tip clearance [5]. As these sensors use a magnetic field to obtain measurements, they can be used outside of turbine casing, depending on casing material, which can be useful as there is no need for a hole in the casing. However, this can cause sensitivity to vibration in the area between the casing and the sensor. Additionally, these sensors cannot be used with all blade materials.

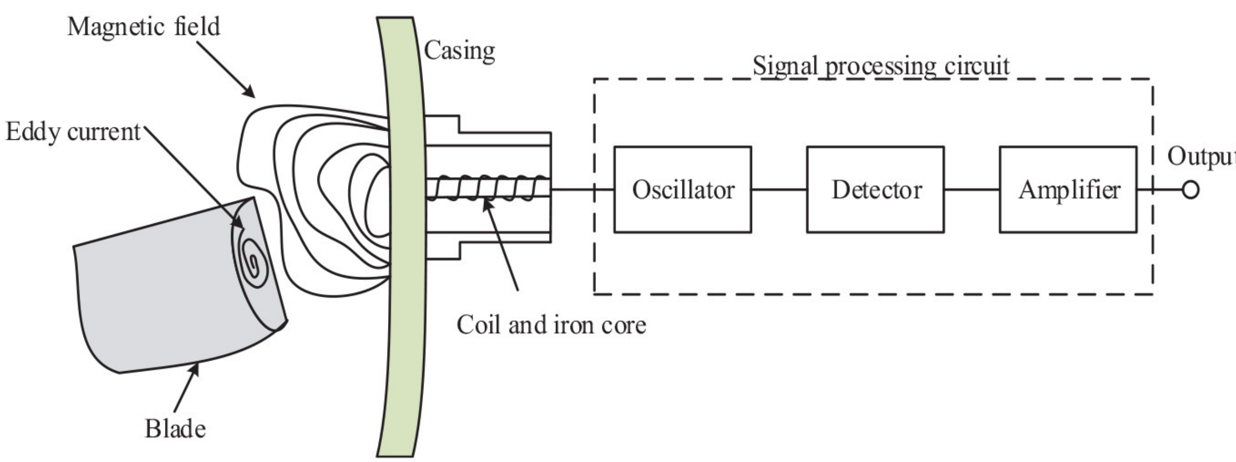

Figure 6: Diagram of the eddy current method [5]

Optical probes can be used to measure blade tip clearance [10]. These probes tend to be more accurate than alternatives, such as capacitance probes. In addition to this, optical probes can measure tip clearance regardless of blade material.

Figure 7 shows the set-up of the Agilis Measurement System V-probe, an example of optical probe used for tip clearance measurement. Unlike other methods of tip clearance measurement used, optical probes perform blade tip clearance calculation using blade tip timing. Using this technology, blade tip shape may not impact readings as much as with other measurement methods. This can be more efficient when creating calibrations for a wider variety of blade tip geometries.

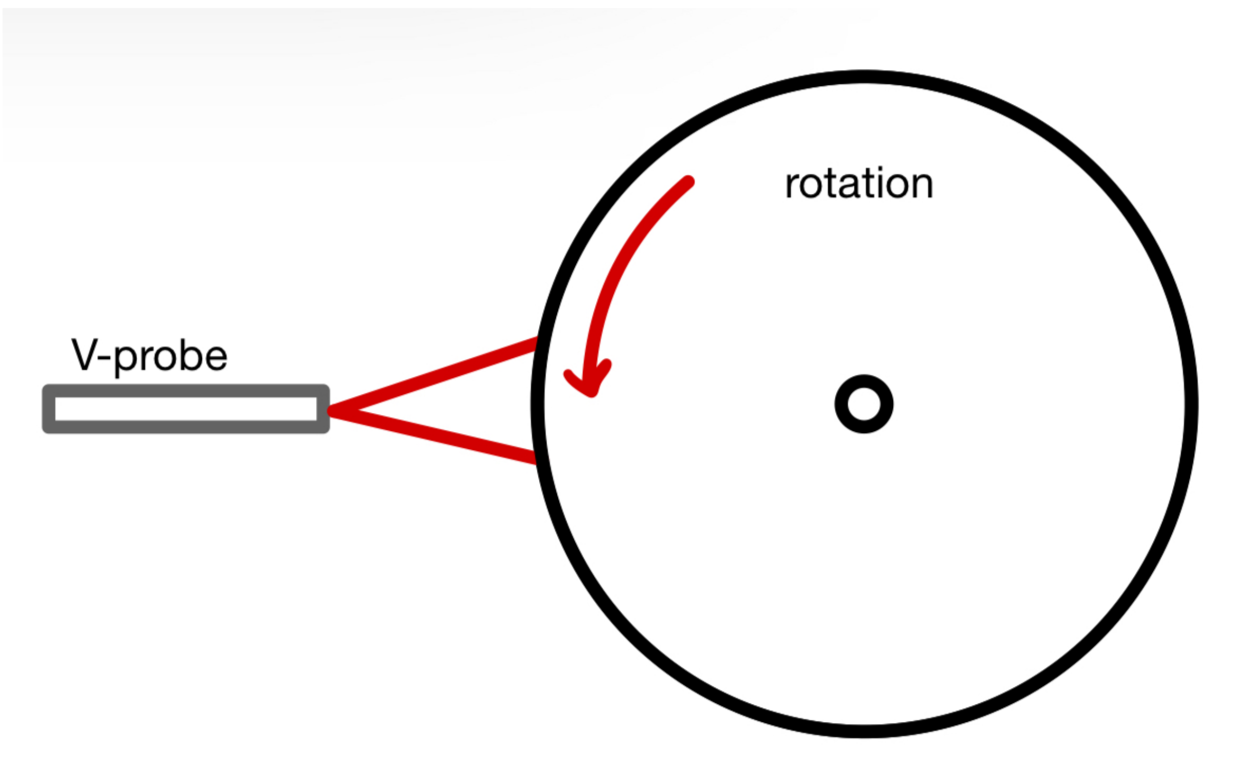

Figure 7: Set-up diagram of the Agilis Measurement System V-probes

Optical V-probes have been run in environments that simulate the vibration, temperature, and pressure that is seen in the turbine [11]. Upon this testing, the probes continued to read consistent results, showing the durability of the measurement system through various environmental factors. However, optical v-probes typically are not resistant to dirt and other contamination within the flow field [12].

Optical V-probes use Arrival Time Analysis (ATA) to determine blade tip clearance. Arrival Time Analysis, or Blade Tip Timing (BTT), is a technique that is used to evaluate the time at which each blade passes by a stationary point. In this case, this point is the V-probe. The probe uses this time (blade arrival time) along with rotational velocity and radius to calculate the blade tip clearance.

This study aims to investigate a different method of measurement for blade tip clearance. With a new method, it is the goal that accuracy will be high enough across a variety of environmental and orientational parameters to decrease blade tip clearance. With a decrease in clearance, an increase in turbine efficiency is seen. This will, in turn, allow for gas turbine operation with less fuel.

1.6 Project Description

Through this project, the use of optical V-probe sensors will be investigated. More specifically, calibration methodology for Agilis V-probes will be designed and outlined for future use in various turbine applications. The probes used have been calibrated and tested on blades rotating at a 24-inch diameter in the past by the manufacturer. For use at Penn State's START Lab, these probes will be used on differently sized disks with rotating blade geometries. For the purpose of this project, calibration methodology will be tested on a spinning rig with a 7.8-inch diameter disk. With the Agilis V-probes, calibration curves from the 24-inch diameter disk are provided. Curves will be obtained on a separate disk to evaluate the impact of disk size on calibration curve coefficients.

Chapter 2 Experimental Setup

2.1 Probe Hardware Setup

To collect accurate blade tip clearance data using Agilis V-probes, linear motion was stabilized along the central axis of the probe. Additionally, motion not along this axis was eliminated to prevent measurement inconsistencies that may cause changes in the angle at which the probe is aligned with blades. A general setup system for probe calibration can be seen in Figure 8.

A linear traverse system was used to allow for linear motion towards the rotating blades. A probe clamp, like the one seen in Figure 9, was used to stabilize the probe against the linear traverse during testing. The clamp pictured was produced using stereolithography (SLA) additive manufacturing. When moving along this linear axis, the probe and its supporting mount moved simultaneously to allow for consistency in the angle at which the probe sits during measurement.

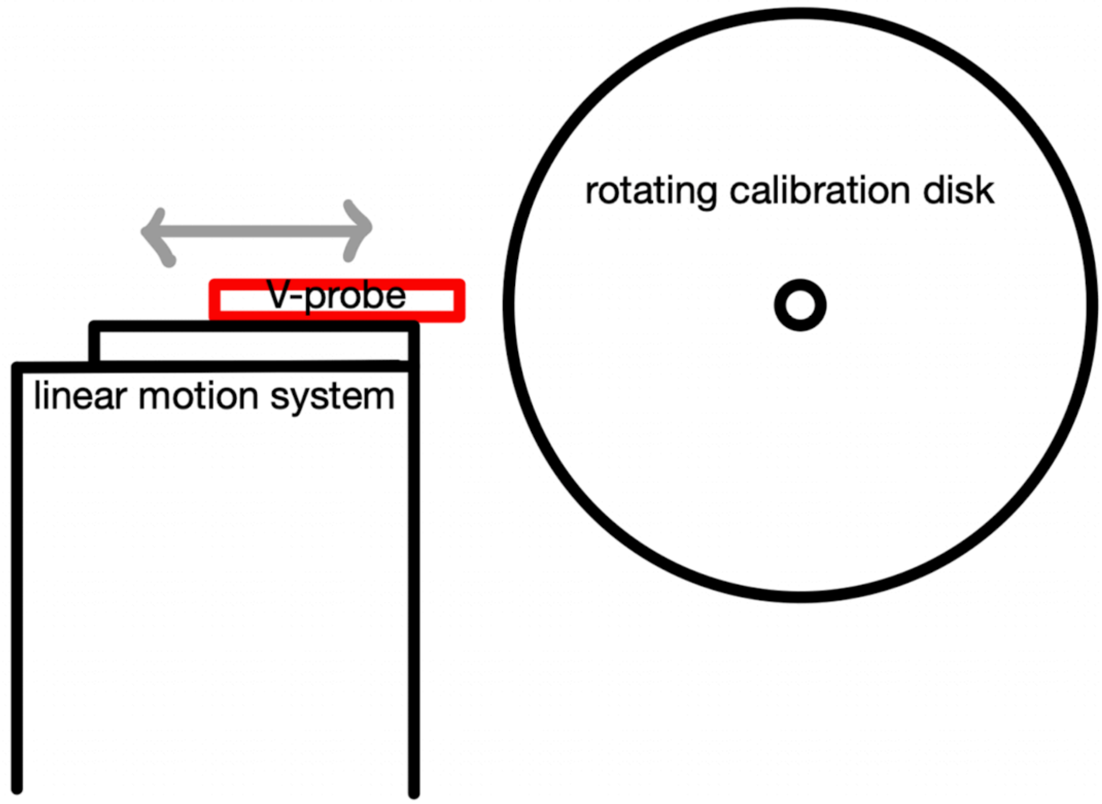

Figure 8: General probe calibration set-up

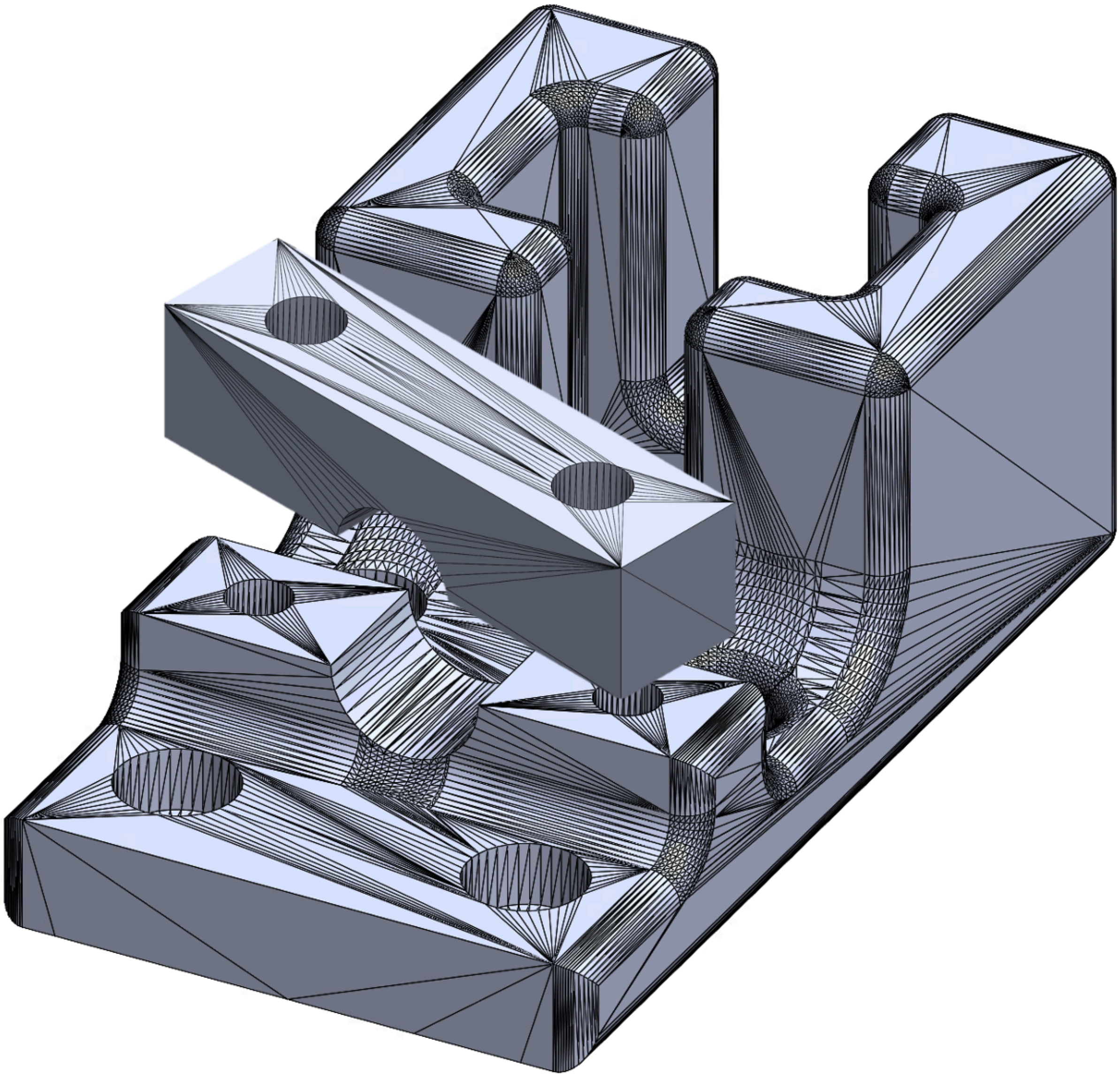

Figure 9: Additively manufactured probe clamp designed for stability

When connecting V-probes to the control computer, various connecting cords were necessary, as seen in Figure 10. Power was supplied through a standard wall outlet. Each Agilis probe was connected to the Laser side of the Laser and Detector (LanD) box through three separate Swagelok connectors: two of these connections receive signals from the probe (one from each beam) and the other connection transmits a beam. On the Detector side of the LanD box, eight cables connected the box to the control computer's input. If probes are operated in high-temperature environments or areas with debris, purge air would also need to be set up using the provided manifold and a standard shop air supply.

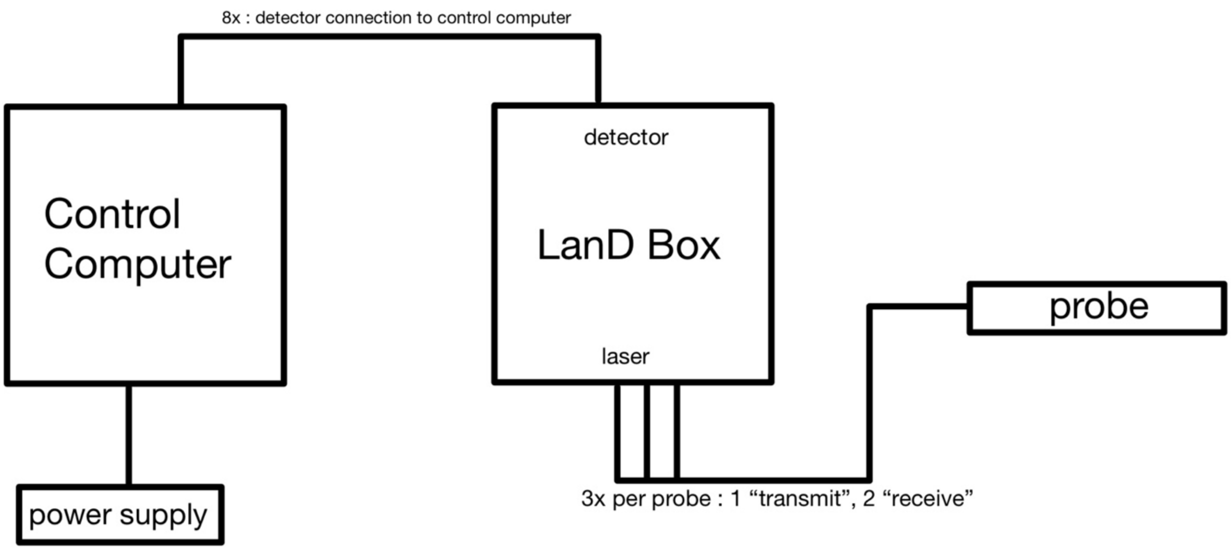

Figure 10: Agilis V-Probe wiring setup

2.2 Probe Software Setup

To power the Agilis V-probe lasers and collect data, a set of various programs in the Agilis c360 software suite were used. To begin, the power switches on both the control computer and LanD box were switched on. The LanD box takes three minutes to reboot and connect to the control computer prior to arming the laser beams. Upon signing in, the c360 "Laser Control" application was launched. When banks are properly configured and the LanD box is connected to the probe and computer correctly, the "Laser Control" window appeared similarly to the window seen in Figure 11, displaying the power supplied to each transmit channel. If these channels are not showing, "Configure Banks" was selected to reserve device then re-configure the banks.

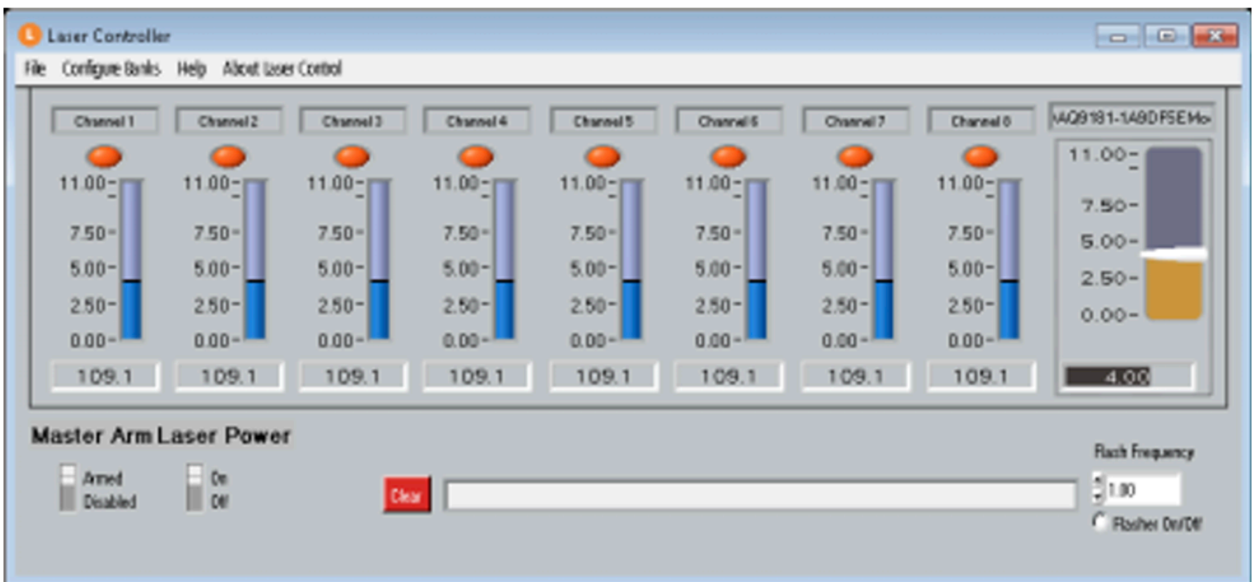

Figure 11: Laser Controller system with properly configured banks

Once the lasers were armed with the provided password and turned on at the "Continuous" setting, the c360 Real Time software was launched. If blades are rotating in front of the probe, a periodic signal appears and syncs up with each passing blade as seen in Figure 12. Different settings in the Real Time program can be adjusted to clean up the signals provided for more accurate analysis and understanding of the data provided.

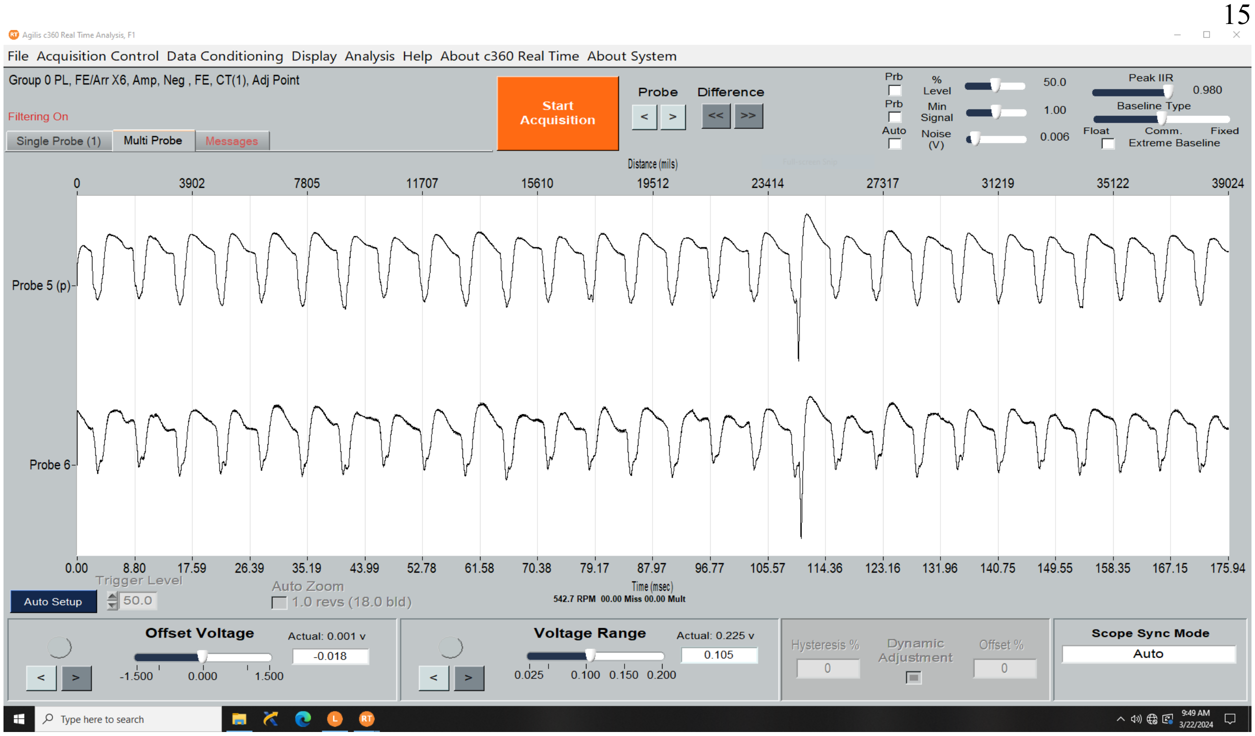

Figure 12: Passing blade signal in Scope Mode

The RealTime software was launched in “Scope Mode” by default. This mode allowed changes to settings such as voltage range and offset, noise, event trigger, etc. “Configuration Editor” from the “Acquisition Control” tab was opened to deselect any probe channels that were not actively used. This allowed for more clear and efficient viewing of signals.

The first thing to check in the Real Time software was that the transmit beams are in the proper order. When viewing the probe signals as a difference, there were two distinct periodic functions with a slight offset. If the signal appearing first was the black line, nothing was changed. If the signal appearing first was the red line, the “left” and “right” connections in the Laser side of the LanD box were swapped.

2.3 Data Acquisition

Once settings were adjusted to view a clean signal, users clicked the "Start Acquisition" button to enter Acquisition Mode. Then, "Clear Map" and "Zero Calculation" were selected to start the data acquisition from a blank template. Upon data acquisition progress reaching 100%, the "Probe/Diff Conversion" window was opened through the "Analysis" tab. In this window, "Simple Difference" was selected as the transfer function type. The average tip clearance read by the probe was be seen in real time.

To calibrate individual Agilis V-probes, the probe was set a known distance away from the rotating blades. Here, this distance was measured using gage blocks. The user entered Acquisition Mode and the "Probe/Diff Conversion" window. After allowing data acquisition to occur for at least 15 seconds at a known tip clearance distance, data was exported as a text file for analysis. "Output" and ".txt" from the Files tab were selected, followed by the correct output directory.

2.4 Probe Calibration and Data Analysis

To determine a relationship between values read by the probe and actual tip clearance, a calibration curve was created for the probe. To create this curve, probe readings were obtained at a variety of known distances from the rotating blades. Gage blocks were used to set the probe at a known distance from blades. Probe readings were acquired and exported as text files. This process was repeated multiple times at increments of ten mils within the probe's clear signal range. The known distance was measured using the same blade each time for consistency.

Once data was exported as .txt files, it was entered into an Excel spreadsheet for easy analysis, as seen in Table 1. An average was obtained for tip clearance reading (labelled with a unit – "mils" seen below) at each known distance from the blades, as seen in Table 1. Then, average probe reading vs. known distance was shown on a scatter plot, as seen in Figure 13. A trendline was created to determine calibration curve coefficients for numerical comparison to test repeatability and consistency.

Table 1: Sample calibration curve data for one known distance in Excel

Probe 6 - Probe 5, Simple Difference, Instance 2					
Raw Data Input, Unfiltered Output					
Blade Average					
UTC seconds	Date/Time		RPM		mils
(01-01-1904 epoch)					
3793984472	34:32.5		536.57		91.274
3793984473	34:32.7		554.73		88.2942
3793984473	34:33.0		533.26		92.1502
3793984473	34:33.1		533.67		90.5566
3793984473	34:33.3		545.08		91.327
3793984473	34:33.5		541.5		90.8427
3793984474	34:33.7		544.16		89.5893
3793984474	34:33.9		537.27		91.8418
3793984474	34:34.2		549.31		91.1556
3793984474	34:34.3		542.52		90.7319
3793984474	34:34.5		538.24		91.3548
3793984475	34:34.7		544.65		89.3731
3793984475	34:34.9		538.12		90.3699
3793984475	34:35.1		540.49		89.1909
3793984475	34:35.3		541.95		90.2224
3793984475	34:35.5		537.33		90.4356
3793984476	34:35.7		544.28		89.5864

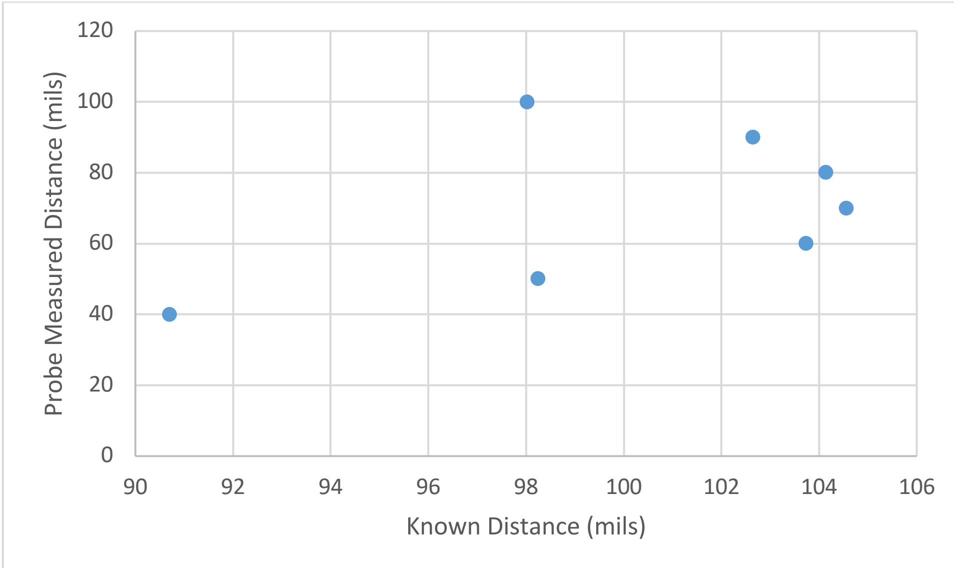

Figure 13: Sample calibration curve

Chapter 3 Results and Discussion

3.1 Results

Multiple sets of calibration data are collected using Agilis laser V-probes within the 40-100 mil range. Excel is used to create calibration curves from this data, as seen in Figure 14. Prior to delivery, the vendor calibrated these probes using a disk with a 24-inch diameter. At the START Lab, these probes are calibrated on a much smaller disk with a 7.8-inch diameter. In the 40-100 mil range, there seems to be a clear drop in tip clearance measured by the probes around the known clearance of 60 mils, which creates a nonlinear shape. In practice, this causes problems with estimating the real blade tip clearance as a second order equation can lead to two possible distances.

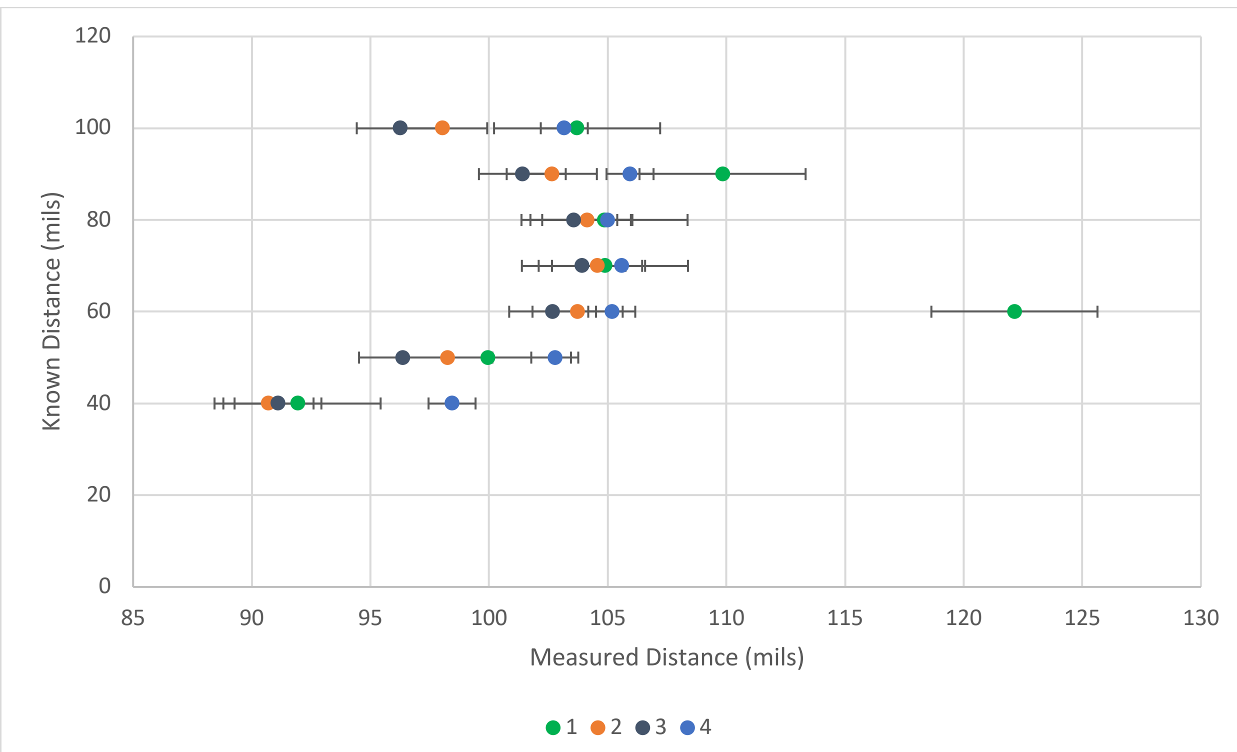

Figure 14: Calibration curve with range bars for 40-100 mil range on 7.8-inch diameter disk

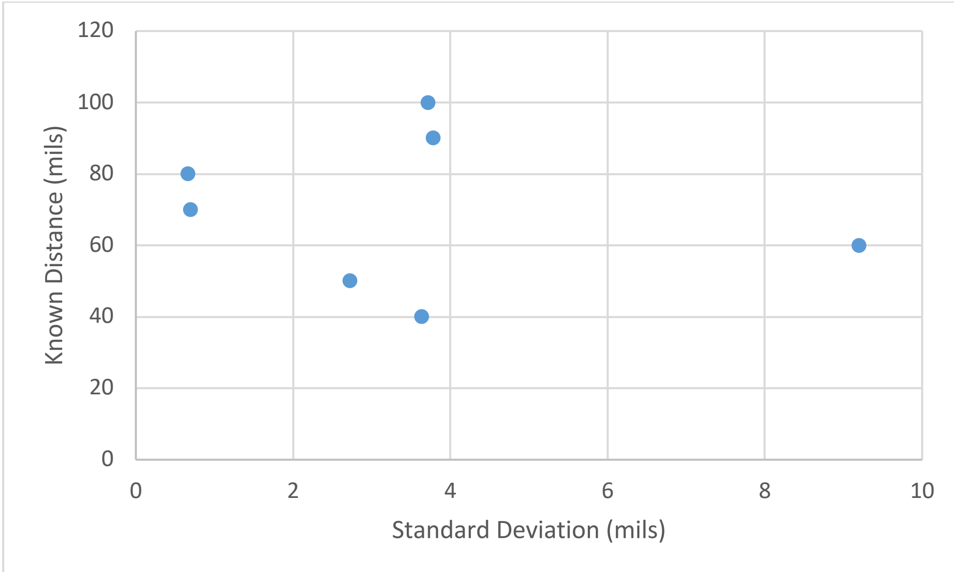

Figure 15: Standard deviation vs. known distance in 40-100 mil range on 7.8-inch diameter disk

Because the calibration curves reach nonlinearity around 60 mils, a lower range is examined. Here, the minimum end of the range was decreased to 30 mils with the maximum end being 60 mils. The same calibration curve generation method is carried out for a lower range of blade tip clearance for comparison with the manufacturer curve in a linear region. This is carried out multiple times for averaging of the calibration curves. The original curves along with the manufacturer calibration curve can be seen in Figure 16, and error bars for these curves can be seen in Figure 17. Figure 18 compares the manufacturer curve with the averaged calibration curve collected from the 7.8-inch diameter disk and shows an overall range. In this zone of known distances (30-60 mils), it appears that the manufacturer calibration curve has a similar initial slope, but the initial decrease in measured value can be seen around a known distance of 60 mils. There also appears to be an offset from the curves generated on the smaller disk.

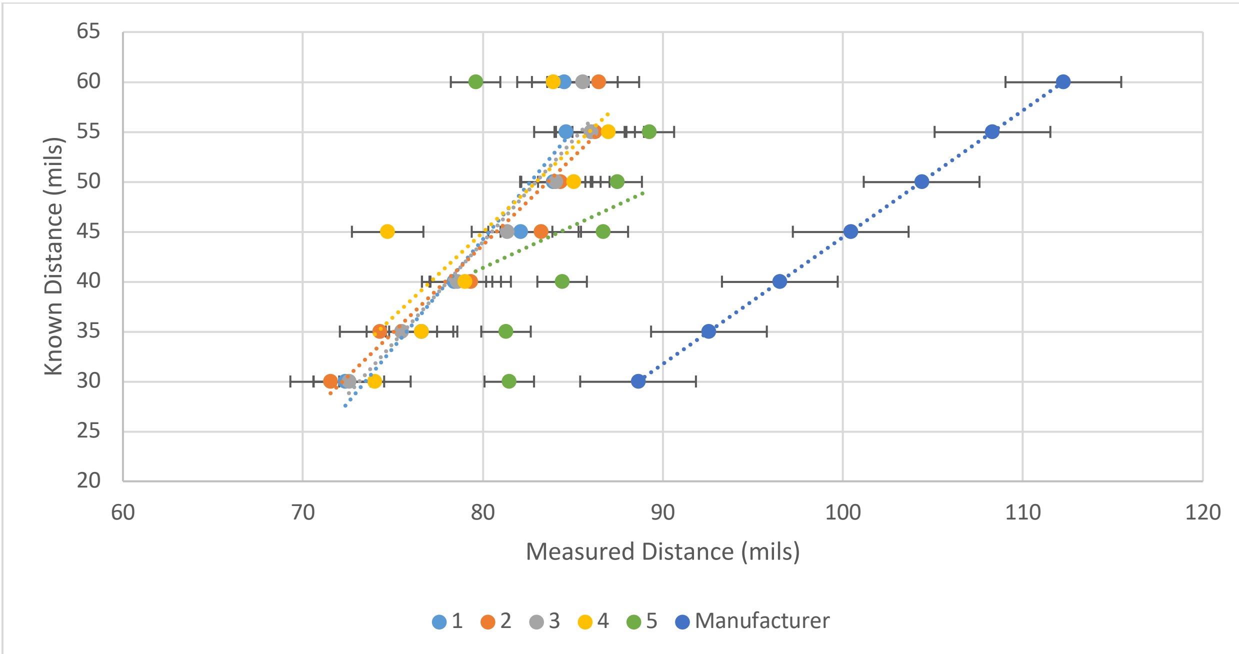

Figure 16: Calibration curve with error bars for 30-60 mil range on 7.8-inch diameter disk

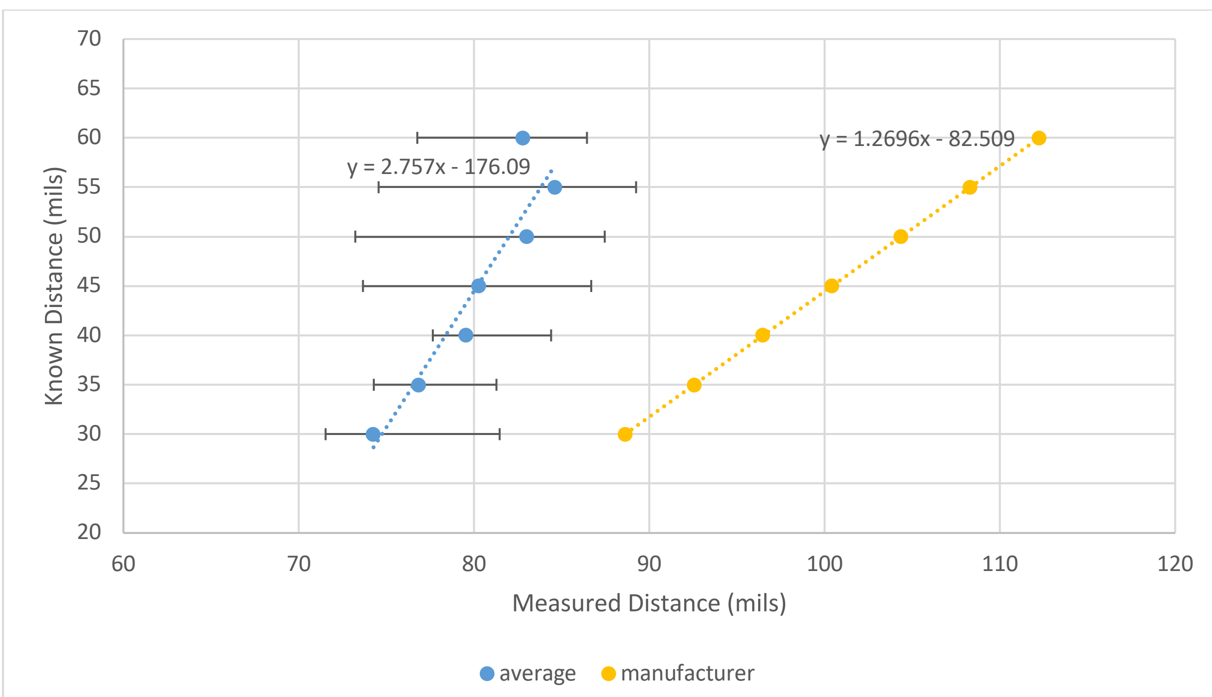

Figure 17: Average calibration curve on 7.8-inch diameter disk with range bars and manufacturer curve from 30-60 mils

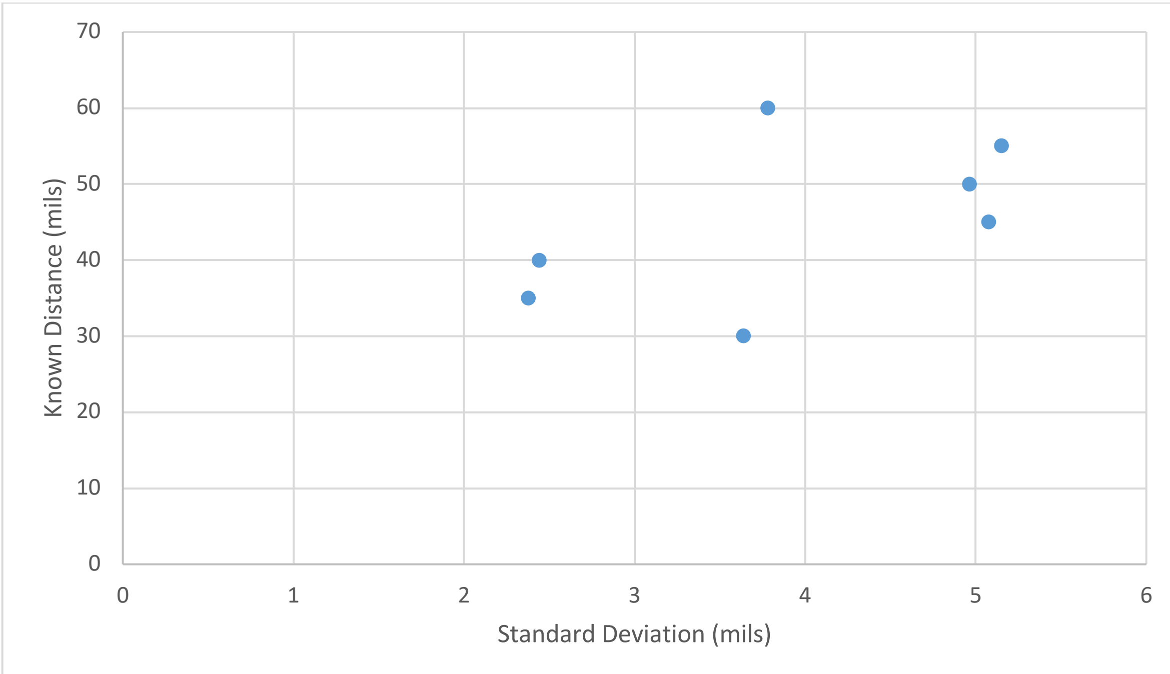

Figure 18: Standard deviation vs. known distance in 30-60 mil range on 7.8-inch diameter disk3.903 inch radius disk

3.2 Discussion

Throughout this study, a calibration process for optical V-probes was developed for blade tip clearance measurement use. The manufacturer, Agilis, initially calibrates these probes on a 24-inch diameter disk, so calibration on a 7.8-inch diameter disk was practiced to examine potential shifts in the calibration curve based on disk size.

The initial calibration curves focused on a range of tip clearance from 40-100 mils. These curves reached a point of nonlinearity around 60 mils. With nonlinear calibration curve trends, it is possible for one distance measured by the probe to correspond to multiple known distances. For this reason, the study shifted to focus on a tip clearance range of 30-60 mils to examine calibration curve behavior in a lower range at which linearity still seems to exist.

The same calibration methods were carried out in the 30-60 mil range and compared with the manufacturer calibration curve. There were multiple differences in these trendlines. The curve generated from the 7.8-inch diameter disk has both a steeper positive slope and an offset from the manufacturer-generated calibration curve. With blade positions derived from arrival time, a direct relationship between disk radius and measured distance can be seen. This explains the offset between the curves generated on the 7.8-inch and 24-inch diameter disks. These differences highlight the importance of V-probe calibration on the proper operating equipment prior to testing to allow for minimization of the measurement errors that come with calibration on varying disk size.

Chapter 4 Future Work

The initial step to move forward is to continue generating calibration curves on the 7.8-inch diameter disk. This will allow for more confidence in the calibration methods used.

To further investigate the accuracy of these probes, it will be necessary to test the probes and obtain calibration curves with varying parameters. Some of these may be environmental factor changes, specifically temperature. The calibration curves obtained above were obtained at room temperature. However, gas turbine engines operate at very high temperatures, so measurement accuracy may be affected. Positional parameters, such as axial position and angular position, could impact probe readings as well. The impact of rotational speed on probe calibration should be investigated. Another factor that should be tested is changes in LanD box input channel for each probe.

Moving forward with these probes in the START Lab, there is an aim to use them for tip clearance measurements within the turbine test section. To do this, the probes will need to be calibrated on the same disk as the test turbine.

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