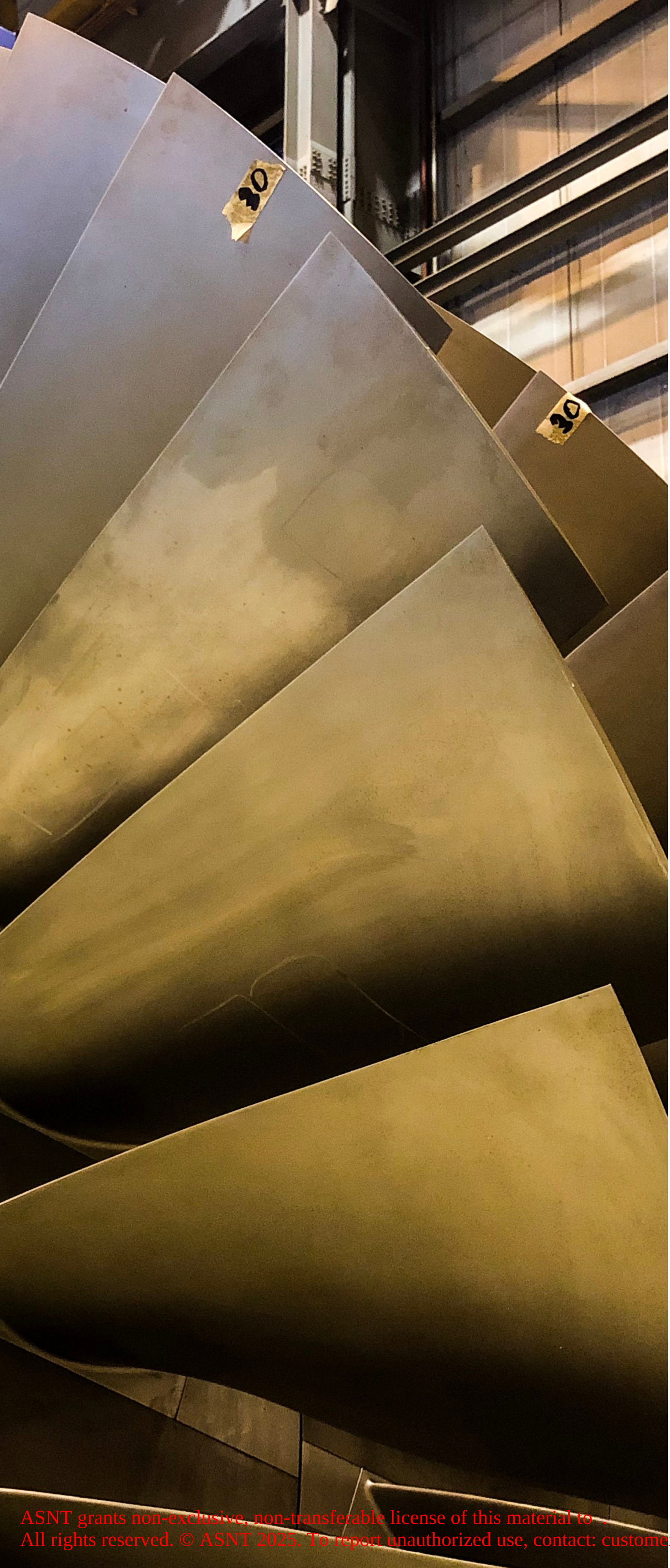
RVI FOR INTERNAL HEALTH MONITORING OF INDUSTRIAL GAS TURBINES

BY PAUL THOMPSON

INDUSTRIAL GAS TURBINES ARE ROBUST, DURABLE, AND DEPENDABLE, BUT THEY CAN DEVELOP PROBLEMS SUCH AS INTERNAL WEAR, LOSS OF THERMAL BARRIER COATINGS, AND PREMATURE PART FAILURES. IF LEFT UNDETECTED, THESE ISSUES CAN LEAD TO SIGNIFICANT UNPLANNED COSTS AND DOWNTIME. TO PREVENT PREMATURE FAILURES, AND AS AN AID IN FUTURE OUTAGE PLANNING, INTERNAL HEALTH MONITORING USING REMOTE VISUAL INSPECTION (RVI) CAN DETERMINE WHETHER COMPONENTS ARE IN GOOD CONDITION AND FIT FOR SERVICE, OR IF ADDITIONAL REPAIRS ARE NEEDED. THE USE OF RVI, WITH A VIDEO BORESCOPE CAPABLE OF ANALYZING AND QUANTIFYING INDICATIONS USNG 3D DATA DISPLAYED IN A POINT CLOUD, ALLOWS FOR MEASURING ANOMALIES WITH ACCURACIES OF 0.001 IN. (0.025 MM). IN SOME CASES, EARLY DETECTION AND 3D ANALYSIS OF INTERNAL ISSUES IN INDUSTRIAL GAS TURBINES HAVE SAVED OPERATORS MILLIONS OF DOLLARS, SOMETIMES EVEN DURING A SINGLE OUTAGE.



Introduction

Industrial gas turbines are the heart of operations where electric power generation, cogeneration of electricity and steam, gas compression, propulsion in marine applications, or a combination of these is necessary for a plant or vessel to operate. While these turbines are incredibly dependable, they have regular maintenance schedules and occasionally forced outages where remote visual inspection (RVI) is required to determine if industrial gas turbines are fit for service, or if additional repairs and maintenance are required. The nondestructive technique of RVI, which is a discipline within the visual testing (VT) method, allows for indirect visual inspections of areas of the fan, compressor, combustion section, and power turbine with minimal disassembly. Auxiliary components and balance of plant (BOP) items such as piping, valves, vessels, and machinery are also inspected with RVI during these outages. When surface indications or discontinuities are detected, extremely accurate indication sizing and 3D analysis are now possible with RVI. The benefits are minimized downtime, increased safety, and maximized return on investments for the operation. This article provides insights on how the proper implementation of RVI technology, and accurate interpretation of the data obtained during an RVI event, can provide valuable diagnostic information on the internal health of a gas turbine.

Direct visual examinations to determine the safety of a situation or the quality of assets have been around as long as eyesight. Visual testing (VT) is thought of as a foundation of nondestructive testing (NDT). VT in industrial applications began in the early 1920s. It was not until 1988 that VT became a certified testing method in ASNT's SNT-TC-1A. However, it was not widely accepted by industry until the European Union Standards Committee incorporated VT in the EN 473 certification standard in 2001. EN 473 was subsequently replaced by ISO 9712:2021(en): *Nondestructive Testing – Qualification and Certification of NDT Personnel*.

To perform effective direct visual examinations, the recommended distance and angle for viewing is to have the eye within 600 mm

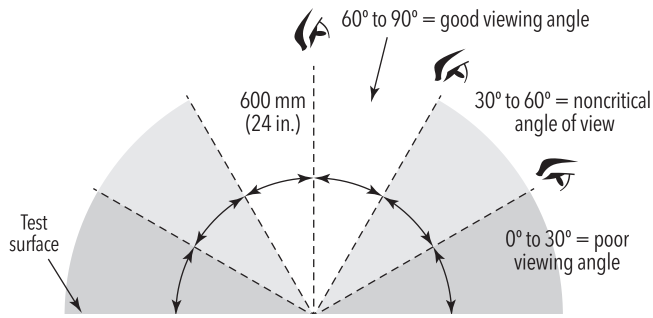


Figure 1. Direct visual testing viewing angle and distance.

(24 in.) of the object and positioned at an angle not less than 30° to the inspection surface, as shown in Figure 1 [1].

Making a direct visual examination to determine the condition of internal components in a gas turbine is physically impossible without significant amounts of downtime and disassembly. As seen in Figure 2, a technician can readily inspect the internal components of a large frame gas turbine. When knowing their internal condition is required, this is where RVI becomes indispensable. It is interesting to note that while RVI is a subdiscipline of VT in SNT-TC-1A and ISO 9712:2021(en) visual testing (methods), both direct unaided visual tests and visual tests conducted during the application of another NDT technique are excluded. This accentuates the importance and value of qualified and certified NDT personnel who are specifically using RVI.

RVI enables the visual inspection of otherwise inaccessible areas or surfaces. The earliest examples were endoscopes that began to be used for medical purposes in the early 18th century. With the advent of cannons, artillery operators would lower a candle on the end of a stick into a cannon bore to determine its condition prior to use. You might see why this could be problematic for the inspector! People soon realized they could only see in straight lines, but if mirrors or fiberoptics were used, the light and image could "go around" corners. From this discovery, the borescope and borescope technology have evolved.

Dr. George S. Crampton developed the first industrial borescope, which was used by the Westinghouse Co. for examining internal turbine components. Inspecting internal surfaces of a turbine rotor were some of the first RVI applications on industrial turbines. While Crampton was a mechanical "MacGyver" of sorts, he used optical instruments in his medical practice as an ophthalmologist and tinkered with optical instruments in his spare time. His work led to the founding of the Lenox Instrument Co. [2].

Today, typical RVI applications with borescopes are inspecting internal components on aviation and

Figure 2. Visual inspection of a GE Vernova large frame gas turbine's fuel lines.

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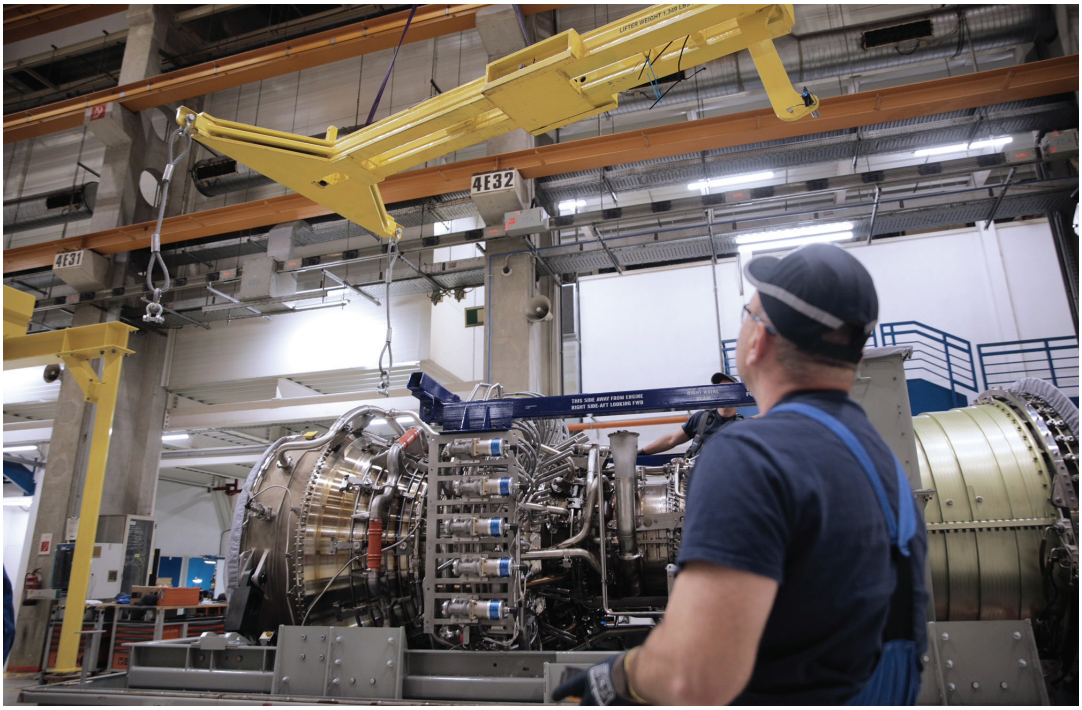

Figure 3. GE Vernova readies an LM6000 aeroderivative turbine for service.

industrial turbines, power cylinders, pipes, tubing, boilers, and heat exchangers, within numerous industrial applications.

Aerospace and power-generation gas turbine operators benefit from RVI procedures, commonly referred to as "borescope inspections." In fact, gas turbines in aerospace and industrial applications are among the largest industry segments that use borescopes. Small port plugs can be quickly removed from the external casing, and a borescope inserted by a technician allows for the inspection of internal stages or areas of the fan, compressor, combustor, power turbine, and related accessories. Borescopes for turbine inspections come in two basic configurations: one with a flexible insertion shaft and one with a rigid insertion shaft. Both types can be configured with or without video capability. This article focuses primarily on flexible video borescopes.

In some cases, industrial turbines were initially developed as aviation turbines. For instance, Pratt & Whitney's FT4000 is the aeroderivative industrial variant of the PW4000, and Rolls-Royce's RB211 is used in both aviation and industrial applications.

Similarly, the GE Vernova LM6000 (LM is a Land Marine designation) aeroderivative turbine shown in Figure 3 was developed from the CF6-80C2 aviation turbine platform. The CF6 has been in use for over 50 years on long-haul flights by Boeing and Airbus. A cut-away of the CF6 as shown in Figure 4 depicts the major section of a gas turbine.

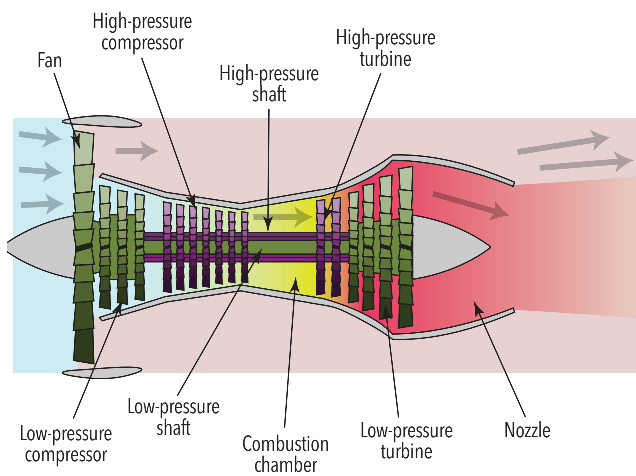

Figure 4. Cut-away view of the major section of a CF6 gas turbine used in aviation.

In power generation, there are also much larger and heavier frame turbines that have higher power output. However, both turbine types operate fundamentally the same, in that ambient air is compressed, mixed with fuel and heat in the combustion section, and then passes through a power turbine section where the energy is extracted. Notice the scale difference of the aeroderivative LM6000 in Figure 3 and the large frame 7HA.03 in Figure 5.

Therefore, it makes sense that RVI inspections on aeroderivative and large frame turbines would be comparable to those conducted on aviation turbines, and indeed they are. A significant difference is that aviation turbines are inspected on

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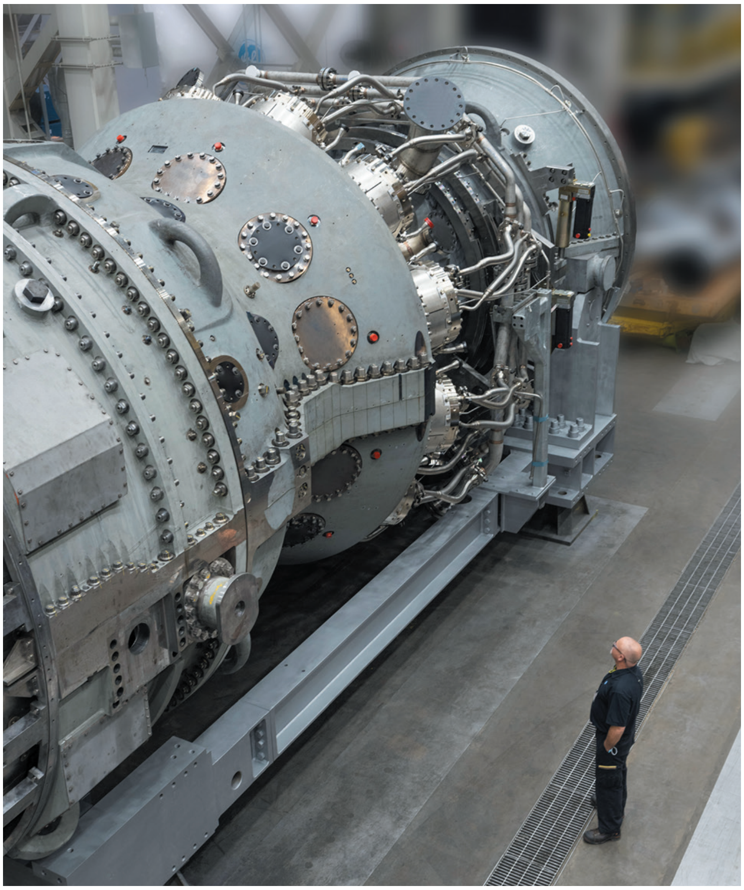

Figure 5. Large frame 7HA.03 GE Vernova gas turbine.

a more frequent schedule to ensure flight safety. Another critical aspect of RVI for both aviation and industrial turbines is determining whether a turbine can operate safely and efficiently until the next scheduled inspection, thereby ensuring maximum uptime and profitability. This often involves needing to make precise and accurate measurements of various types of surface indications. A thorough understanding of RVI techniques, and the equipment being used, is critical for collecting accurate image data to make these assessments.

Background

It is crucial to have RVI equipment that meets examination requirements, can accurately measure indications and anomalies on demand when needed, and is standardized to provide indication size analysis traceable to precision measurement standards like those at the National Institute of Standards and Technology (NIST). This ensures accurate decision-making data can be obtained.

Even with the best equipment in the world, training—or lack of training—of RVI technicians significantly impacts the quality of the inspection data obtained. Training for RVI technicians is no less critical than it is for technicians in other NDT disciplines such as ultrasonics, radiography, and electromagnetics.

When preparing for a borescope inspection, some critical factors must be considered to help ensure success. Ask yourself:

- Is the camera and entire video borescope system serviceable and standardized to provide indication size analysis traceable to precision measurement standards like those at the National Institute of Standards and Technology (NIST)?
- Does the RVI technician know how to inspect the cleanliness of the camera and optical tip adapters, with both fixed and removable optical lenses?
- Is the technician trained and qualified to use the equipment, and do they understand the inspection requirements?
- Is their training complete on both the RVI system and the asset to be inspected?
- Has the performance of the technician and RVI equipment been evaluated with a Probability of Detection study, or has a Gage Repeatability and Reproducibility (Gage R&R) [3] been completed on assets requiring accurate detection and measurement analysis?
- Does the technician know the necessary diameter and length of the flexible camera shaft to ensure access through all borescope ports and to reach the farthest inspection points?
- What is the required travel path of the camera to the inspection area? Are guide tubes, push poles, or other accessories required to deliver the camera to the inspection site?
- Does the technician know what to do and what *not* to do if the camera becomes stuck in a turbine?
- What is the internal environment in the inspection area? Is it hot, cold, toxic, explosive, or corrosive?

Each of these are key factors to be aware of when performing an RVI task, and they should all be addressed in a training program. One must understand the benefits—and risks—of performing RVI with the proper equipment and trained technicians versus best-in-class equipment and inadequately trained technicians.

RVI Data Collection and Analysis

In these examples, you will see where RVI measurements were taken, and that the measurement data obtained was accurate. However, the measurement data was also very wrong. How can measurement data in the same image obtained with best-in-class RVI equipment be both accurate and wrong at the same time?

There are caveats one can learn to mitigate with training. Two critical ones are that the XYZ data points used to achieve measurement data must exactly map the shapes and contours of the surface to be analyzed, and the measurement cursors must be accurately placed on these data points.

First, a measurement image captured with a video borescope must accurately depict the underlying measurement data determined by the calculated XYZ coordinates, ensuring that each camera pixel correctly maps the surface points. If the point cloud data—all XYZ data points which are stitched together to form a point cloud—precisely matches the surface points, accurate measurements can be made using the XYZ coordinates in that point cloud. Note that in Figure 6 the point cloud data on the image's right side accurately depicts the surface points as seen in the white light image on the left. Using point cloud image data for measurements can result in more accurate and precise measurement data.

Pivoting a point cloud image on the X, Y, and Z axes allows the technician to evaluate the point cloud's health; in other words, does the point cloud data exactly portray the surface being viewed? This can be done by pivoting the point cloud image on the video borescope's display or doing the same in PC-based remeasurement software.

If the point cloud data quality is low, it will not accurately depict the actual surface geometry. There may be holes, or missing data, and there may be wavy or extremely lumpy areas in the point cloud even when the surface being imaged is flat. The point cloud data must accurately represent the area of an image that is to be measured. Accurate placement of the measurement cursors is also critical and can be validated, and relocated if needed, in the point cloud.

Here are examples of two separate RVI tasks showing how, even with good image data quality, obtaining accurate measurement data yielded the wrong measurement data. More importantly, we will see how to resolve these errors.

In the first example, Figure 7 shows a stereo measurement of a tip-to-shroud clearance being used to determine the wear of a power turbine's blade tips. The measurement type being used is referred to as a *depth* measurement. It can be thought of as measuring the distance to or from a reference plane established by placing three cursors on a reference surface. Then, by placing a fourth cursor on a point, one can calculate the distance of that fourth cursor above (+) or below (–) the reference plane. Blade tip-to-shroud clearance is important data for decision-making regarding the efficiency of the power turbine and assessing the need for repairs.

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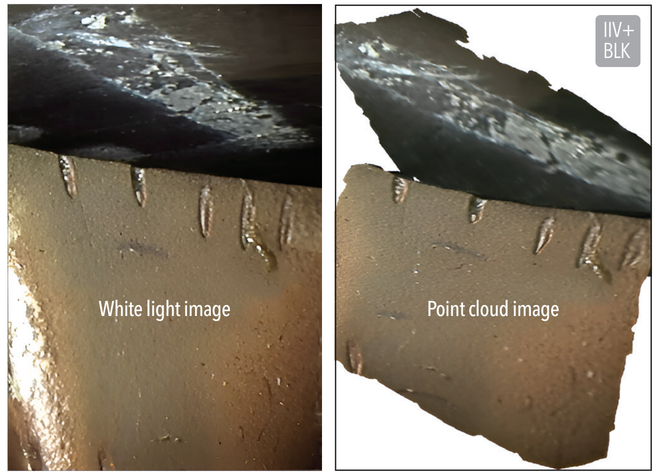

Figure 6. Power turbine shroud (darker top part of image) and blade tip (bronzish lower part of image) as seen in a white light image (left) and an XYZ 3D point cloud (right).

As seen in Figure 7, three points of a mathematical reference plane *appear* to be on the shroud's surface: the cursors labeled 1,2, and 3. (Pay particular attention to the plane's cursor labeled 3.)

The fourth cursor, labeled 4, is placed on the tip of the blade and provides a measurement from the reference plane on the shroud to the blade tip.

In Figure 7, the measurement data of 0.031 in. (0.787 mm) may be considered accurate because cursors 1, 2, and 3 for a reference plane appear on the shroud (the darker surface in the upper portion of the image), and the measurement cursor (cursor 4) appears to be placed on the tip of the blade (the bronze-colored surface in the lower portion of the image).

When the stereo measurement system does not have the capability to generate a viewable 3D point cloud, moving the fourth cursor around the measurement plane can help establish a valid placement of the reference plane, as indicated by minimal, if any, distance variations from the reference plane. This step is often overlooked in stereo measurements that do not offer a point cloud view.

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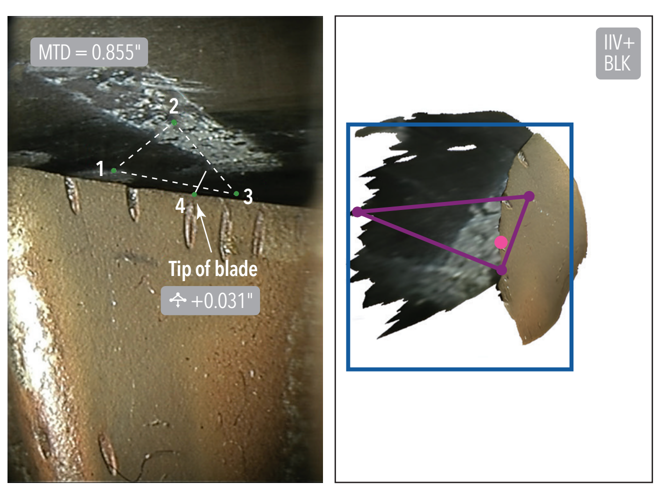

Figure 7. Power turbine blade tip-to-shroud, measured with a stereo image–reference plane data was not validated. The darker top part is the shroud of the combustor; the bronzish lower part is a power turbine blade.

However, when observing the cursor placement in a fully surfaced point cloud image, it becomes evident whether the point cloud has low data quality and if cursors have been accurately positioned on the data. Reviewing both metrics in the point cloud can help increase accuracy and precision of the collected measurement data.

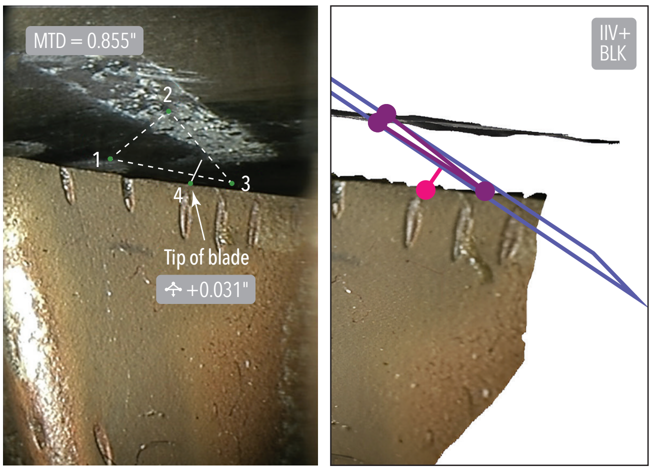

Figure 8. Power turbine blade tip-to-shroud, measured with stereo. Measurement data found to be in error by reviewing the point cloud.

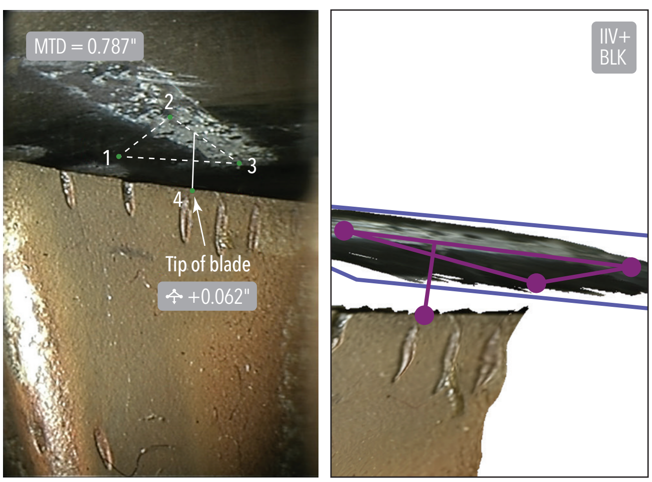

Figure 9. Power turbine blade tip-to-shroud, measured with stereo. Measurement data error corrected by correctly placing the reference plane's cursors on the shroud while reviewing the point cloud.

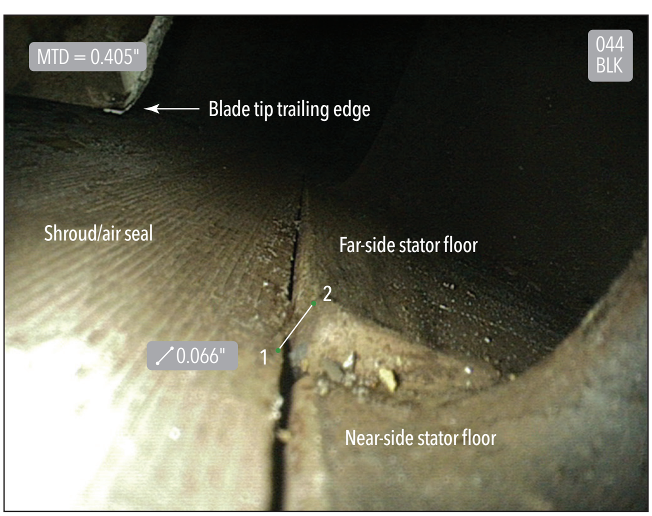

Figure 10. White light image of compressor section with stator section to be measured for rocking.

In the example in Figure 7, the technician was not trained in how to validate the measurement data in a stereo image, nor were they trained to review the point cloud data and the cursor placement upon the data. This led to providing a blade tip-to-shroud clearance data of 0.031 in. (0.787 mm).

When a measurement system's point cloud is reviewed and pivoted in X, Y, and Z onscreen, it immediately becomes obvious that a common measurement error has been made. Note in Figure 8 that when viewing the 3D data in the point cloud image, the cursor labeled 3 of the measurement's reference plane (the lower, far-right magenta cursor) was placed on data from the tip of the blade, not on reference plane data for the shroud.

Note that the reference plane's blue lines are an extension of the three cursors used to establish the reference plane. When that plane is tilted away from the actual surface of the shroud, the tip-to-shroud gap measurement appears smaller than it actually is. Because the data quality in the point cloud is extremely high, this presented an accurate measurement. Because cursor 3 of the reference plane was inaccurately placed on the tip of the blade, and not on the shroud, the results obtained are also wrong. This exemplifies a scenario where good measurement image data quality resulted in an accurate measurement but also produced incorrect measurement data.

To correct this error, the reference plane cursor labeled 3 has been moved in the point cloud in Figure 9 and placed on the shroud, which yields a different result of 0.062 in. (1.57 mm). This 0.031 in. (0.787 mm) discrepancy may seem small, but using this incorrect measurement data can cost the asset owner hundreds of thousands of dollars if the equipment is taken out of service prematurely for unneeded repairs. Also, leaving erroneous measurement data unaddressed while the asset remains in service can lead to efficiency losses in the power turbine, impacting proper operations and resulting in revenue losses.

The RVI image used in the second example is in the compressor section of a large frame gas turbine used to turn a massive electricity generator at a power plant. In this type of industrial gas turbine operation, downtime can bring losses of millions of dollars a day and may also result in penalties and fines, sometimes as much as US$1 million [4].

This power plant was in a planned outage. An RVI task was scheduled to evaluate if the stationary vanes in the compressor section were properly fixed in place or if they were becoming loose and beginning to tilt, or "rock." Some stator rock is allowed, though significant damage and unplanned forced outages can result when limits are exceeded.

As previously discussed, to increase accuracy and precision of RVI measurement data, the XYZ point cloud data must exactly replicate the data points on the surface being observed. Proper placement of the cursors is critical.

In Figure 10 we see one measurement cursor, labeled 1, on the shroud on the left, and the second cursor, labeled 2, on the shoulder of the far-side stator yielding measurement data of 0.066 in. (1.676 mm).

In Figure 11, notice that the geometry of the point cloud exactly matches the surface geometry as observed in Figure 10. The data integrity of the point cloud would allow for accurate measurements. Also note the placement of the cursors in the point cloud. The RVI task requires measuring the offset of the stator floors, not the offset of the stator floors to the shroud.

Even if shroud-to-stator were the required measurement, the measurement in Figure 11 is not taken perpendicular to the shroud's shoulder, nor is it entirely on the stator floor. It would be close to impossible to measure perpendicularly from the stator floor to the next stator floor using a two-cursor length measurement.

In addition, the data was not validated in the point cloud prior to providing the operator with the results. Repairs were being discussed prematurely, which could have resulted in additional outage days and the loss of millions of dollars per day in revenue, along with reduced availability of electricity for the grid.

Once more, this illustrates a situation where the measurement data is perfectly accurate but also yields incorrect measurement results.

To resolve the measurement data errors, the technical guidance for making this stator rock measurement with RVI was reviewed. The best measurement type to use would again be the *depth* measurement. This measurement type measures the perpendicular distance to or from the reference plane. The reference plane would be placed on one of the stator floors, and the fourth measurement cursor would be placed on the other stator floor.

In Figure 12, a three-cursor depth reference plane (depicted as a dotted-line triangle and labeled 1, 2, and 3) was placed on top of the far-side stator floor, and the fourth measurement cursor, labeled 4, was placed on top of the near-side stator floor. This is seen in the white light image on the left half of the image.

The resulting measurement data was 0.029 in. (0.736 mm), a difference of 0.037 in. (0.939 mm) from the original measurement data provided to the plant manager. Having the correct data allowed the plant to come back online without extending the outage, while also saving millions of dollars.

A magnified view of the point cloud image depicted in Figure 13 enables validation of the

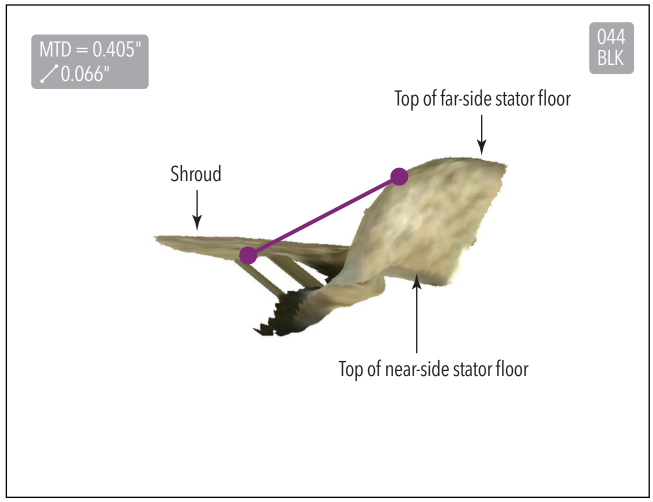

Figure 11. White light image of compressor section with incorrect measurement type and cursor placement.

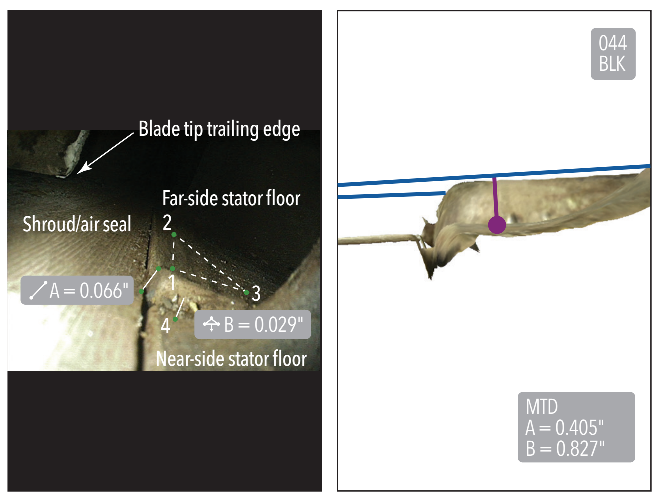

Figure 12. On the left side of the image is the white light image of compressor section with depth measurement. On the right is the point cloud image of depth measurement.

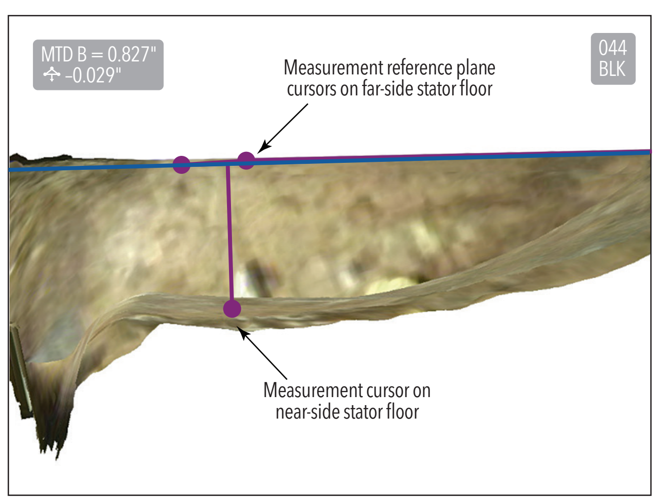

Figure 13. Full point cloud image of area being measured. Point cloud data depicts exactly the geometry of the surfaces being measured.

correct placement of cursors on the surfaces and confirms that the point cloud data precisely replicates the surface being measured.

Summary

In summary, RVI using video borescopes can assess the internal health of industrial gas turbines and help avoid false calls that could lead to increased downtime and significant unplanned expenses.

Although current generation video borescopes require a significant initial investment, they can deliver a substantial return on investment (ROI) even after just one inspection event.

The results provided can be more accurate, leading to safer and more efficient operations with lower ownership and operational costs.

The key to achieving this is to have the proper equipment operated by trained and qualified technicians, certified by their employers to perform specific RVI tasks on a particular asset. ME

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ROBOTIC VISUAL INSPECTION IN CONFINED SPACES

BY EKKEHARD ZWICKER, BRANDON DEBOER, MARKUS WEISSMANN, AND ANTOINE CHEVALEYRE

Robotic visual inspection presents a promising solution to the challenges posed by confined space inspection, offering enhanced efficiency, accuracy, and safety.

Introduction

The latest advancements in robotic visual inspection technology—including the generation of digital twins, the tagging of inspection data within asset models, and the implementation of semi-autonomous control—demonstrate how robotics can effectively tackle the challenges of inspecting confined spaces. Localization technologies such as lidar (light detection and ranging) and 3D modeling are key for effective confined-space navigation. Maintaining image quality in robotic visual inspections is also important, to ensure compliance with industry standards.

The experimental validation that follows evaluates the technical capabilities of robotics and pole cameras for confined space inspection. This includes visual examination, ultrasonic thickness readings, and 3D surface scans. The integration of digital twin technology streamlines data management and facilitates post-inspection analysis.

Robotic visual inspection ultimately offers numerous benefits, including high-quality and reproducible data, reduced outage time and costs, process improvement through automation, and increased safety by minimizing human entry into confined spaces.

Challenges with Confined Space Inspection

Inspecting confined spaces presents several challenges and risks due to the unique nature of the environment, including [1, 2]:

- **Limited access.** Confined spaces are typically difficult to reach and may have restricted entry points, making it challenging for inspectors to thoroughly examine the area.
- **Poor visibility.** Many confined spaces have limited lighting or may be completely dark, hindering the ability to see potential hazards or defects.
- **Restricted movement.** Inspectors may face difficulties maneuvering within confined spaces due to narrow passages, obstacles, or equipment obstructions.
- **Communication challenges.** Communication between workers inside a confined space and those outside can be challenging due to physical barriers or poor reception, increasing the risk of accidents or delays in emergency response.
- **Time constraints.** Inspections in confined spaces often require careful planning and coordination to ensure the safety of personnel. Time constraints may arise due to limited availability of access or the need to complete inspections quickly to minimize disruption to operations.
- **Training requirements.** Inspecting confined spaces requires specialized training and expertise to identify potential hazards and implement safety protocols effectively. Lack of proper training can increase the likelihood of accidents or errors during inspections.
- **Documentation and reporting.** Proper documentation of confined space inspections is crucial for regulatory compliance and risk management. However, maintaining accurate records can be difficult, especially in remote or hazardous environments.
- **Emergency preparedness.** In the event of an accident or emergency inside a confined space, rescuing workers can be complex and time-consuming. Inspectors must be adequately trained in emergency procedures and have access to the appropriate rescue equipment.
- **Regulatory compliance.** Confined space inspection must adhere to stringent safety regulations set by authorities such as OSHA (the Occupational Safety and Health Administration) in the US. Failure to comply with these regulations can result in legal repercussions and jeopardize worker safety.

Addressing these challenges requires careful planning, appropriate training, and the use of advanced technologies and safety measures to ensure the effectiveness and safety of confined space inspections.

Limitations of Remote Visual Inspection

Remote visual inspection (RVI) conducted in confined spaces such as pressure vessels, reactors, and boilers, whether using a remote-controlled crawler or a camera mounted on a pole, often relies heavily on manual control. The crawlers are piloted remotely, data is captured manually, and reports are subsequently created by transferring this information into predesigned templates. This disconnected approach presents several challenges. First, there is no direct link between the captured data and its specific location within the asset. Second, this manual process (Figure 1) demands significant additional effort to leverage the data for internal processes and integrate it with the digitalization strategies of asset owners and operators.