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AUTOMATED INSPECTION OF TURBINE BLADES: CHALLENGES AND OPPORTUNITIES

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Abstract

Current inspection methods for complex shapes and contours exemplified by aircraft engine turbine blades are expensive, time-consuming and labor intensive. The logistics support of new manufacturing paradigms such as integrated product-process development (IPPD) for current and future engine technology development necessitates high speed, automated inspection of forged and cast jet engine blades, combined with a capability of retaining and retrieving metrology data for process improvements upstream (designer-level) and downstream (end-user facilities) at commercial and military installations. The paper presents the opportunities emerging from a feasibility study conducted using 3-D Holographic Laser Radar in blade inspection. Requisite developments in computing technologies for systems integration of blade inspection in production are also discussed.

1. Introduction

The factory automation of compressor and turbine blade manufacturing for aircraft jet engine power plants is a process that involves the integration of a variety of subsystems into the complete manufacturing and refurbishment cycle. Once processing parameters, envelopes for variation and control strategy are reliably established, perhaps the most important area of challenge lies in the rapid sensing and acquisition of dimensional and surface quality attributes of blades that validate the design, processing and control strategy.

The success of new technology development programs such as Integral High Performance Turbine Engine Technology (IHPTET) and the economic viability and competitiveness of current military and commercial engine blade production rests heavily on the ability to develop and implement cost-effective automation solutions that are highly reliable, and lead to consistent quality components at minimum cost. The ability to rapidly achieve automated blade inspection opens up a world of possibilities that translate to our ability to retain vital information on individual blade attributes for utilization both, upstream (in the design and processing iterations) as well as downstream (in process control, field use and maintenance). An integrated product-process development (IPPD) approach like the one envisioned in the IHPTET program has the potential to lead to a 50% or greater reduction in manufacturing costs[1]. In such advanced engine programs, the criticality of consistently meeting design parameters and tolerances in manufacturing, tracking changes during maintenance and overhaul, and validation of manufacturing process models cannot be overemphasized. An automated blade inspection system on the shop-floor when integrated with a design and processing database through a Computer-Aided Design (CAD) 'reverse-modeling' capability, could be responsible for accomplishing a large portion of that cost reduction through its support of IPPD and Knowledge-Integrated Design Systems of aeroengine components.

1.1 Present Blade Measurement Technology:

In current forged compressor blade and investment-cast turbine blade (Figure 1) manufacturing environments, all metrology and in-process inspections are performed off-line by large pools of human labor. One recent plant study performed by ERIM determined that as much as half of the plant labor were involved in manual inspection and rework of blades. Dimensional inspection is limited to use of hard go/no-go guillotine gages that contact a forged or cast blade at several consistent locations, at each of which the 'fit' is probed by the inspector, and rework locations marked- a process that takes even the expert up to three minutes per blade.

A human inspector is highly flexible, and has relatively fast recognition and decision-making capability. However, the task of manual turbine blade inspection is particularly challenging because of the inspector's high susceptibility to a lack of concentration over several hours, which results in a relatively poor average performance of the person. Furthermore, different inspectors have been known to arrive at different dimensional inspection results, producing variable final batch outputs that are unpredictable and inhibit process and resource optimization. In such an environment, statistical process control is especially difficult to implement. The critical nature of the application to commercial and military aircraft propulsion requires that parts be inspected 100-percent. Present coordinate measurement machines (CMMs) impose an inherent and obvious limitation on the inspection throughput achievable, except for process certification and qualification. By 100-percent inspection of blades, an automated sensor system can be used to control even a slow decay in quality that cannot be found easily by off-line statistical checks.

Following represent typical tolerances for key compressor blade sections used in advanced engine programs:

Twist	+/- 30'
Platform	+/- 0.18 mm (0.007 in)
Chord	+/- 0.25 mm (0.01 in)
Thicknesses	+/- 0.09mm(0.0035 in)
LE Profile	+/- 0.05 mm (0.002 in)
Bow	+/- 0.05 mm (0.002 in)

1.2 The Economic Case for Automation:

The following represents a typical production inspection scenario at a leading aircraft engine compressor blade forging plant (also applicable to a typical turbine blade investment casting facility):

- The plant possesses tooling capacity for approximately 1600 different blade designs, of which about 400 designs are processed in batches at any given time, with a weekly production rate reaching between 60,000 and 90,000 parts.
- Compressor blade forgings of titanium may be up to 0.45 m (18 in) in length and 0.2 m (8 in) wide, with the majority (80%) fitting an envelope size of 0.20 m (8 in) length and 0.06 m (2.5 in) width. A typical compressor blade assembly is shown in Figure 2.
- Each blade is inspected twice by human inspectors using two sets of gages (one spare for use when the other is being re-certified or recalibrated). The plant's metrology equipment investment per blade design is slightly over $400,000.
- Work areas are often filled with dust, smoke, noise, vibrations, or heat that can additionally affect measurement system design, and consequently, cost and system life.
- The cost of quality (i.e., scrappage) ranges from $500-$1000 per blade.

Despite operating under strict quality control guidelines, high quality requirements have frequently been met at such plants by scrapping large quantities of blades[2]. Thus, there is potential for realizing significant cost savings by interception of nonconforming product earlier in the manufacturing cycle using automated inspection.

1.3 Sensor Selection Criteria:

Following minimum criteria are considered important in sensor selection for automated blade inspection:

- Inspection speed or cycle time
- Part throughput
- Sensor parameters such as resolution, repeatability, accuracy, range ambiguity, etc.
- Robustness to plant-floor conditions (temperature, vibrations, dust, operator handling)
- Costs and life (acquisition, installation, training, maintenance)
- Flexibility in measurement of blade designs

2.0 Non-Contact Blade Inspection Systems

2.1 State-of-the-Art:

A recent ERIM study[3] determined that many 3-D measurement systems are available commercially for industrial and metrological inspection, most based on optical sensing techniques such as: (1) intensity modulation laser scanners, (2) stereo, (3) structured light sensors, (4) Moire sensors, (5) holographic sensors, and (6) interferometric sensors. Most commercially available 3-D sensors are based on the triangulation principle, including structured light, stereo and Moire. 3-D sensors employing laser modulation and interferometry have also been commercialized, but to a lesser extent.

An ERIM-developed intensity or amplitude modulated laser scanner, supported by the CYTO-HSS pipeline cellular-array image processor, has been demonstrated in forging operations for missile nose cone components[4,5]. The scanning system circumvents the complex computational and conceptual difficulties associated with 3-D reconstruction of the imaged component from a limited number of camera views. One major shortcoming of laser scanning technology identified was the high level (and hence, expense) of maintenance required to keep the highly polished mirror and optical surfaces clean in the forging environment. In stereo imaging, triangulation is the most commonly used method for 3-D sensing. However, stereo techniques require some common reference point for the two camera views to be correlated together- if the surface being inspected is a smooth, continuous curve (as in airfoils and blades), such a point may not exist. Even when located, the accuracy in determining the single point is limited by the resolution of the camera, and does not provide information about other points on the surface in question[6]. Compared with laser scanning, Moire techniques[7] are known to provide better dynamic-depth range and repeatability, while using an eye-safe white light. They are best suited for inspection of objects that have limited depth such as the body panels of automobiles. Besl[8] has discussed details of evaluation criteria and applications of several optical range imaging sensors. Holography-based sensors, capable of meeting the challenges of precision industrial inspection. One such system is 3-D Holographic Laser Radar (HLR), which is discussed in greater detail in the following section. While structured light active triangulation 3-D sensing is a very flexible technique, there is a risk of shadowing and obscuration occurring, particularly for objects with step and pole-like features as are often encountered in inspection in the vicinity of the airfoil platform[3]. A new 3-D sensing product from Perceptron, the LASAR[R,9], couples laser radar technology with a precision scanning mechanism and control/display software. The result is a system with a programmable field of view that can simultaneously capture both a 2-D image, based on a standard reflectance phenomena, and a 3-D image based on range data. Olympus[10] has recently introduced a limited capability for performing off-line measurement of manufacturing defects on blade surfaces by using memory-stored wire-frame models that are 'superimposed' on the captured image of a blade.

2.2 Holographic Laser Radar:

ERIM has recently experimentally demonstrated 3-D Holographic Laser Radar[11] (HLR) a technology derived from synthetic aperture radar[12], that shows promise in meeting some of the most stringent accuracy, resolution and performance requirements of a blade production environment. The equipment setup and image recovery process are illustrated in Figures 3 and 4. HLR uses a frequency-tunable laser source (such as an argon dye laser) and holographic recording methods to recover digital 3-D representations of imaged objects. Essentially, the sensor measures the 3-D complex object spectrum by gathering data at different spatial frequencies (up to 64 have been demonstrated at ERIM). At a given wavelength, a 2-D (X-Y) slice of the object spectrum is measured using a detector array that is placed perpendicular to the line of sight towards the object origin. Changing the measurement wavelength, a different slice of the object spectrum is acquired which is off-set in the ranging direction. Thus, by sweeping through a set of wavelengths separated by a constant amount over a total allocated bandwidth, a cube-like volume of Fourier data are gathered. Using the inverse Fourier transformation, a 3-D image of the object is formed.

2.2.1 HLR Sensor Attributes for Blade Inspection:

A preliminary technology assessment performed by a concurrent engineering group at ERIM[3] has revealed that the HLR technology effectively addresses several challenges in blade inspection through the following features of the sensor:

(1) The angle-angle measurement accuracy of the sensor is decoupled from the ranging accuracy, which is important when large parts are to be measured to a high degree of accuracy. The sample permits different sampling densities in the angle-angle and range directions, providing both, dimensional and surface finish information.

(2) An absence of imaging optics as well as scanning mechanisms (i.e., no moving parts) further enhances the desirability of HLR in production inspection of blades. The HLR samples the object light field array directly with a CCD detector array, and the positioning of the detector pixels in a detector array can be very accurate.

(3) If a collimated beam or plane wave is used as the reference, the image formed by 3-D Fourier transformation is in a rectilinear format. This feature is unlike most other types of 3-D sensors discussed above which produce images in polar format or non-linear grid, requiring extensive coordinate transformations for conversion into a usable geometric object representation.

(4) When a point source is used as the reference, its location provides a fixed reference point from which all 3-D measurements are made. This is critical for metrology applications such as parts-to-CAD models, where images from different views must be fused together.

An ERIM HLR sensor was used in a feasibility exploration for initial dense surface profile image collection, as well as to characterize the requirements of HLR technology applied to turbine blade inspection. The 3-D images of both, investment cast and forged blades were acquired by varying the following parameters to determine optimal operating conditions: range resolution, range ambiguity interval, and angular resolution.

2.2.2 Sensor Design and Economic Issues:

Forged titanium compressor blade leading edges are a special subset of dimensional measurements inspection because of the difficulty posed by specular surfaces that challenge other competing measurement technologies (Moire interferometry, laser triangulation, etc). Any solution for this problem can likely be applied to castings, wax models and die cavities. HLR performance data for a variety of surface finish characteristics resulting from investment cast, forged-shot peened, and machined blades is presently being evaluated to determine optimal equipment operation bounds, so as to generate the sensitivity and dynamic range requirements for precision metrology applications. Other design issues that need to addressed in inspection, include the scalability for measuring larger objects, and sensor stability in the production scenario. As a coherent sensor, mechanical stability within the HLR and between the sensors and test object must be kept to a small fraction of an optical wavelength. Phase coherence must be maintained not only over the integration time of each spectral measurement, but over the entire imaging sequence through all the measurement wavelengths. This requirement necessitates stringent vibration isolation and the use of an enclosure to minimize air turbulence.

The HLR sensor can be effectively designed to address the metrology requirements of at least 80% of forged and cast blades, which fall within the 0.2 x 0.06 x 0.025 m (i.e., 8 x 2.5 x 1 inch) size envelope. To meet future desired measurement accuracies of up to 0.025 mm (0.001 in) on the airfoil and blade dovetail platform, would require an extremely large number of measurement points over the objects. The slopes of the blades, however, vary gradually, which may allow fairly coarse spatial sampling in the X and Y directions. Moire sensors cannot take advantage of this feature because of the tight coupling between the angle and range measurements.

An economic analysis of automated blade measurement cell using HLR is presently being performed, considering the projected life cycles of key system components. A production sensor incorporating the 3-D HLR technology is projected to cost between \$50,000 - \$100,000. Additional costs quantifying the impact of the sensor technology on the measurement workforce, production line balance, plant layout and process flow changes in a forging or casting facility, as well as other in-plant implementation and culture issues, are also being addressed.

3.0 Automated HLR Blade Inspection Workstation

3.1 System Requirements:

The aim of an automated metrology and inspection system for turbine blades should be to integrate the components into one complete system. The integrated system should have the computer processing, data storage, and retrieval power needed to inspect, assemble and control all tasks without significant human intervention. An automated blade inspection workstation (Figure 5) incorporating 3-D HLR, as envisioned by us, would consist of four major building blocks:

- Parts handling system that positions blades for inspection and final sorting,
- Laser source system to generate radiation,
- Detector array that converts reflected radiation into a signal or data for host computer processing, and
- Host computer with operator interface and electronic linkage to blade design database,
- An image processor for analysis and decision making.

3.2 Part Fixturing and Orientation:

The HLR sensor provides output data in terms of 3-D rectilinear coordinates for each sample point, as opposed to multiple transformations from polar coordinates that are required for laser scanners. By generating dimensional measurement data on the front/back surface area of the airfoil, it is possible to provide the equivalent measurement capability of not only the contact-type guillotine gage, but also the combined (and potentially enhanced) measuring capability of the blade thicknesses, bow, twist angles, and orientations relative to platform.

3.3 Software Requirements:

A formidable task in developing a systems solution for automated inspection of turbine blades lies in addressing software requirements for registering data from multiple images, extracting and mapping metrics into the gaging measurements and features of interest to the user. This task could also involve interaction with commercial surface mapping and visualization software, in order to determine optimal data density for accurate surface reconstruction and subsequent comparison with CAD and surface design databases. The key would be to determine the approximate X-Y sample spacing required to extract desired surface contour measurements.

3.4 High-Speed Image Processing and Sensor Fusion:

Automated surface and 3-dimensional inspection of turbine blades in a production environment requires real-time-mode image processing, as the number of operations required to achieve defect recognition and metrological interpretation of sensed data tend to be enormous. For example, a high-resolution 3-D HLR image of an entire turbine blade can generate approximately 4 Mbyte/sq in. for a 0.0005 in sample spacing. Decreasing the spatial frequency of the sample points reduces the data size, however, at the expense of accuracy in locating edges. It would be a waste of time to first store dense blade image data into an image memory, and then process it later by accessing the image memory. Thus, it is a requisite in automated blade manufacturing/inspection operations that a fast method be deployed with adequate hardware support such that the completion of image acquisition implies the completion of the image processing (or at least preprocessing). Current trends indicate that a 200-MIPS microprocessor and a 1 gigabit memory chip are soon to become available to meet such image processing challenges, well before the end of the century if lithography limits and other difficulties in each generation are overcome smoothly[13].

4.0 Conclusion

The study has demonstrated that the key technologies and system components for realizing fully automated inspection capability for accomplishing dimensional measurement and defect location in compressor and turbine blades already exist. A systems design, engineering and integration approach is required to evaluate proposed inspection methods in greater detail and to develop alternative methods to satisfy manufacturing and metrology support requirements of commercial and military users. A fully automated Holographic Laser Radar inspection system could dramatically outperform the current manual inspection process by improving the consistency of the inspection process and raising the quality of the blades in service.

5.0 Acknowledgement

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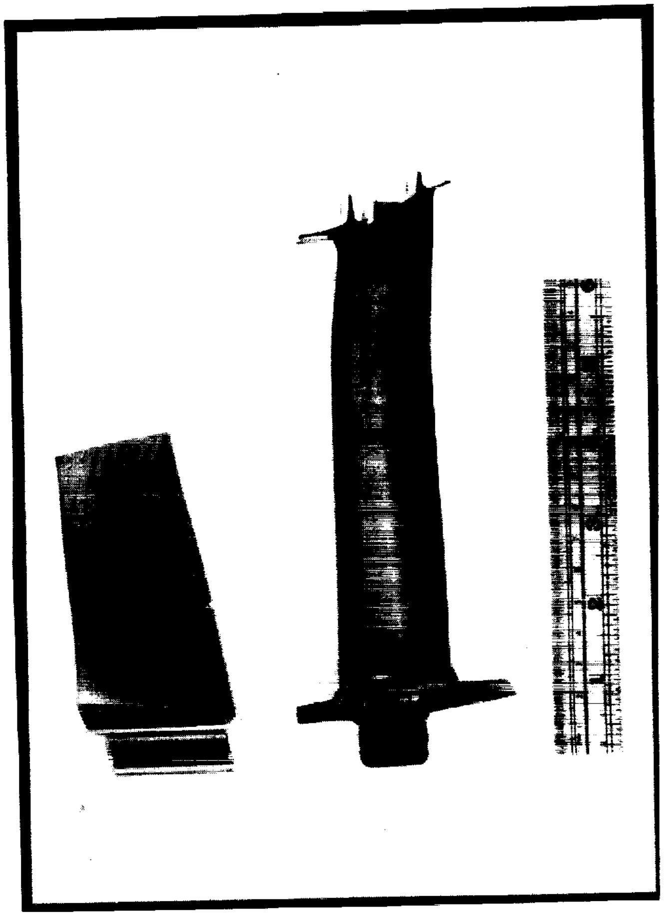

Figure 1. Forged Titanium Compressor Blade (left) and Investment Cast Inconel Turbine Blade (right).

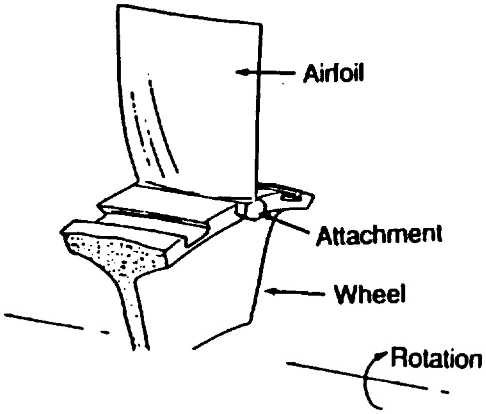

Figure 2. Compressor Blade Features and Assembly.

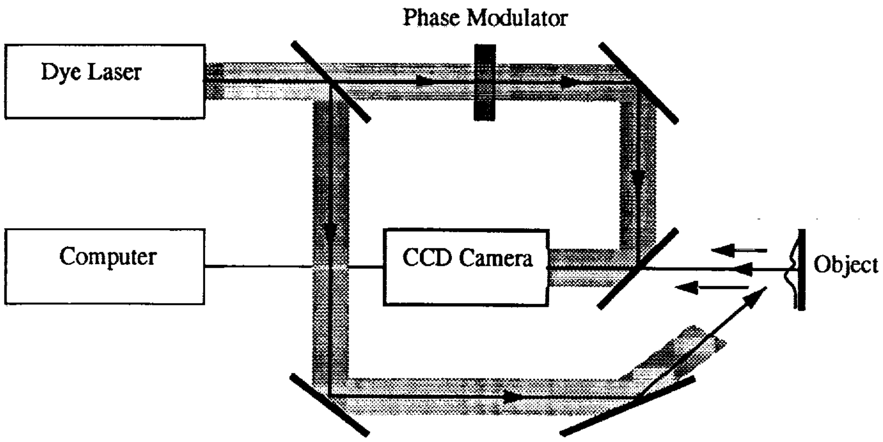

Figure 3. HLR Experimental Setup.

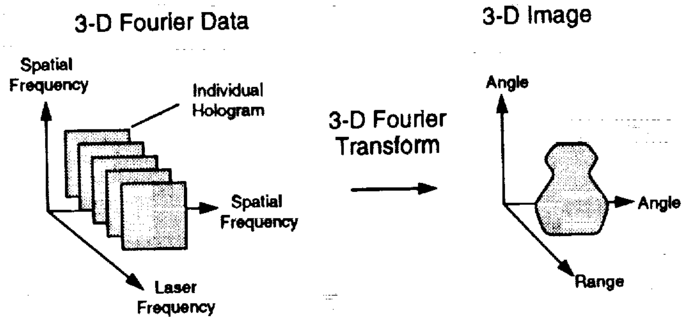

Figure 4. Relationship Between Collected and Recovered Images in 3-D HLR.

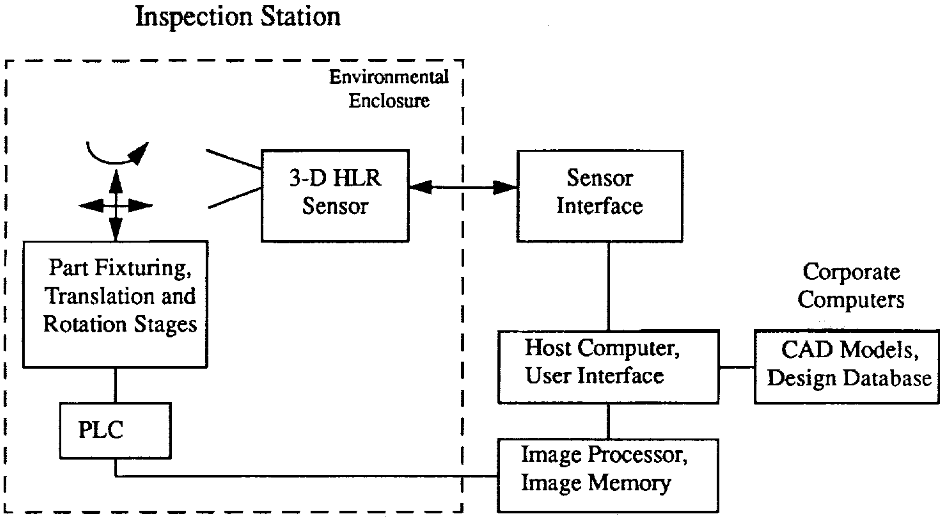

Figure 5. Non-Contact Automated Blade Inspection Workstation Setup.