RFC AUTOMATED INSPECTION OVERVIEW

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ABSTRACT

The RFC Inspection System uses eddy current and ultrasonic techniques to perform automatic inspection of gas turbine engine components. Current flaw size requirements are 0.010 inch (length) x 0.005 inch (depth) surface connected cracks and 0.020 inch diameter penny shaped, mal-oriented internal voids. Successful and reliable detection of these small flaws requires sophisticated inspection equipment and techniques. Details of both the eddy current and ultrasonic inspections will be presented along with the philosophy and reasons supporting each component of the inspections. Inspection components presented will include: part dimensioning, probe calibration, adaptive scanning, threshold detection, signal processing, and flaw position correlation. Additional material will be presented highlighting the problems and solutions associated with a sophisticated, automatic inspection system.

INTRODUCTION

The RFC inspection system performs completely automated eddy current (EC) and ultrasonic (UT) inspections of gas turbine engine components. Efforts have been made to incorporate the advantages of current and newly developed inspection techniques and to allow incorporation of techniques developed in the future. The automation of standard NDE methods requires adaption and modification of existing manual and semi-automated inspection methods and, in some cases, the development of completely new techniques. The details of the resulting automated inspection methods will be presented.

During the development of the inspection system, considerable effort was made to make the EC and the UT systems as similar as possible. Mechanically the systems are very similar due to the choice of a squirter for UT. The ultrasonic and eddy current inspection algorithms are also very similar thus most of the techniques presented in this paper will focus on EC, however, where there are differences the UT techniques will be presented. The topics to be covered are:
1) Calibration of the instrument/probe
2) Part dimensioning
3) Survey mode and Select mode inspections
4) Eddy current nulling
5) Adaptive scanning techniques
6) Algorithm portability

CALIBRATION

An outline of a typical inspection is shown in Figure 1. To assure that the system is performing correctly a probe calibration/check occurs as the first step in the inspection of every geometry. The main object of calibration is to determine: is the probe/instrument combination working as it was when the scan plan was written? If not, can allowable (small) changes be made to make the signal conform to that determined earlier? This definition of the purpose of calibration was developed through much discussion during the program. It is not the purpose of calibration to compensate for all variations nor to derive the proper instrument settings needed for detection and sizing.

SCAN PLAN HIGHLIGHTS

- ENTER + VERIFY PART + SERIAL #
- MOUNT AND LOAD PART + PROBES
- START
- GEOMETRY #1 FORWARD
- GEOMETRY #2 FORWARD
- ...
- UNLOAD + FLIP PART
- START
- GEOMETRY #1 AFT
- GEOMETRY #2 AFT
- ...
- UNLOAD PART
- END

FIGURE 1. Outline of the inspection sequence for the RFC System. Calibration occurs at the beginning of each geometry.

The calibration procedure begins when a probe is automatically picked up (there is no probe changing in UT). The first thing the system does is to take the probe to the calibration block where all of the calibration takes place. In EC the first step is to create a liftoff signal and to rotate the liftoff signal into the horizontal component of the impedance plane. This is accomplished by fitting a best fit line to the liftoff signal, and then calculating the angle of rotation needed to make the line horizontal in the impedance plane. The phase angle is then rotated and another set of liftoff data is taken for confirmation. In UT, the alignment of the transducer/squirter combination is checked by
scanning the two gimbal axes to obtain the maximum front surface response and checking to see if the angle of this response is within allowable tolerances. If the angle is only slightly off, the axes can be offset to accommodate the mis-alignment. If a large mis-alignment is found, the scan is aborted.

Next the probes are scanned across artificial flaws (EDM notches for EC and side-drilled holes for UT). The position yielding the maximum response is found and compared to a predetermined position. If the difference is out of tolerance the scan is aborted. Then the gain of the NDE instrument is adjusted to produce a signal amplitude specified by scan plan. The gain adjustment allows for day-to-day variations in the electronics. It assumes that the different probes and instruments behave similarly. Thus, the gain adjustment must be within a certain range. A probe requiring an unusually large adjustment will cause the scan to be aborted. Finally the signal-to-noise ratio is checked to see if it is within defined tolerances. Additionally, for EC, the parameters needed for bolt hole centering are obtained, and if needed, a null value is recorded (these will be discussed later). For the UT inspection, two additional checks occur. First the water flow rate is measured to assure adequate water flow to the squirter. Next a check is made for the presence of air bubbles as any air seeping into the squirter water system can form air bubbles that eventually flow out the squirter nozzle, appearing to the system as a flaw.

The calibration procedures are executed every time a probe is picked up. Also, any or all of the procedures can be executed just before the probe is returned to the probe holder thus verifying the validity of the preceding inspection. Again it should be emphasized that the primary purpose of calibration is to assure that the inspection system is performing as it was designed. Only small compensations are allowed.

PART DIMENSIONING

In the very beginning of an inspection the operator enters and verifies the part number and serial number. At this point top and side views of the part are displayed for the operator to compare to the part awaiting inspection. Many of the parts are significantly different from each other so no mix-up could occur. However, the air seals are sometimes difficult to distinguish from each other as are the 8th, 10th, and 12th HPC disks. Additionally, the graphics point out features to help the operator distinguish the forward and aft sides and the axial orientation of the part. Thus, most of the time the correct part will be placed in the correct orientation on the fixture jaws. But to safeguard the system (i.e. prevent collisions), and to assure of a reliable inspection, part dimensioning occurs to detect any mistakes. Dimensioning consists of: checking for the proper part, checking for forward/aft side up, checking for axial orientation, and checking for inspectability of the part (warpage, missing features, etc.).

Dimensioning is accomplished (in EC) by using low frequency (500 kHz), absolute coil probes. These probes are spring loaded with the support structure around the coil constructed of plastic. Figure 2 shows a typical dimensioning probe. The presence of metal is detected by monitoring the liftoff signal produced by the coils as they are moved near metal. To check to see if the proper part is placed on the jaws, several part parameters are checked. These may include part height,
bore diameter, part diameter, etc. Typically the dimensioning probe is moved straight down towards the part surface. An ending position and a desired position are designated in the scan plan. The probe will stop moving if it senses metal or it reaches its ending position. If a liftoff signal is received the probe stops and the position where the liftoff signal occurred (no the position where the probe stopped) is compared to the desired position. If the probe reaches the ending position then it is assumed that the wrong part (or no part) has been placed on the fixture. The spring loaded coil allows for the momentum of the mechanics when stopping. Tests have shown that the 0.25 inch maximum movement of the spring can accommodate a linear feedrate of up to four inches/second. Other unique features on the part allow the system to determine if the forward or the aft side is facing up. In particular the anti-rotation tangs found on the HPC disks have proven to be very helpful for this. The operator is expected to orient the part on the turntable such that the zero-degrees position, usually indicated by two small dimples, falls along the laser line generated by the alignment laser (Figure 3). This should provide alignment within about two degrees. However, many parts have features such as offset holes, and offset anti-rotation tangs that allow the system to orient the part itself. Finally, key geometry positions can be checked to determine if the part is inspectable. For example, on a compressor disk, the height of the web region can be measured at various places to determine if the variations are within the range of accommodation of the surface probes.

FIGURE 2. Dimensioning probes used in the RFC System. The coils are embedded in the spring loaded plastic tip of the probe.
The information obtained by the various dimension algorithms is displayed for the operator. Thus, if a part is determined to be uninspectable, the out-of-tolerance dimension information is available for the operator. A typical resolution for the position determination in dimensioning is less than 0.001 inches for EC. In the UT system the procedure is the same except that a front surface echo is looked for within a defined time gate. The resolution for UT position determination is less than 0.005 inches.

SURVEY/SELECT MODE

After dimensioning has assured of part inspectability, and calibration has determined that the probe/instrument is working correctly, the inspection of a geometry begins. There are many conceivable methods of scanning an engine part. In a manual scan the inspector would move the probe across the geometry looking for any variability in the NDE signal. He may vary the scanning rate through the movement at a specific region. An automatic system must scan in a predetermined manner. The human eye/brain performs signal averaging automatically, at any time, while the automatic system can signal average only by making repeated scans, and only if instructed to do so. Finally, a human can ignore a "blip" in the signal either by recognizing the characteristics of the signal or by rescanning the area. To an automated system a "blip" is a flaw signal. Extensive signal processing must occur to distinguish blips from real signals and this seldom occurs in real time. The RFC system has been designed to incorporate the advantageous techniques utilized by the human inspector as well as the advantages of an automatic inspection. This is accomplished by dividing the inspection into two parts: a survey mode where areas of suspect flaws are defined by rapid scanning through the geometry looking for signal threshold excursions; and a select mode where information about the waveform is gathered and signal processing takes place.

FIGURE 3. A laser is used to draw an alignment line on the engine parts.
In the survey mode the geometry is usually scanned in a spiral or helical pattern. This allows for a continuous, non-stop, scan while providing complete coverage of the area. When the waveform sampler receives a signal with an amplitude that exceeds a designated level, the mechanical controller is immediately signalled to record the positions of all axes by a hardware interrupt from the sampler. This process continues until the end of the geometry is reached at which time the mechanical controller sends all of the recorded positions to the Inspection Module Computer (IMC). The system records all threshold excursions. Some of these may have been electronic noise, surface noise, or bubbles (in UT). A position correlation algorithm is executed to weed out extraneous or noise indications and define the areas where several indications correlated as suspect flaw regions (Figure 4). The correlation plays a very important part in reducing the number of false calls.

After the correlation if suspect flaw regions are found the select mode is activated. The select mode positions the probe at the beginning of the suspect flaw region. Then several waveforms are obtained at this position and averaged to improve the signal-to-noise ratios. A peak detection algorithm then finds either the vector magnitude (EC) or peak amplitude (UT) of the signal. The position of the peak is also calculated and recorded. Next the probe is indexed some incremental distance (usually around 0.010 inches) and more waveforms are obtained and averaged. Again the peak and its associated positions are recorded. This process is repeated until the end of the suspect flaw region is reached.

At the end of the suspect flaw region the positions of the peaks are once again put through a correlation algorithm to determine if a correlation exists and/or how many different correlated flaws exits. The flaw length is compared to a minimum flaw length and if it is large enough a flaw is called out. At this point the probe is positioned at the position of maximum response and a sizing routine implemented.

**FIGURE 4.** A section of the bore of a disk is represented showing survey, correlation, and select modes. Correlation of two or more threshold excursions is based upon the proximity of the corresponding positions.
The advantage of a two phase (survey/select) inspection process over a single pass inspection is that the threshold levels set in the survey mode can be reduced nearly to the noise level. Some noise indications may occur. Most of these will fall out in the correlation process. The select mode completes the flaw verification process helping to further eliminate false calls while employing signal processing techniques to further define actual flaws. The main disadvantage of the two phase process (aside from its greater complexity) is the additional time required. However, suspect flaws will not occur with great frequency if the inspection parameters are appropriately set, so the additional time should not be great.

PROGRAMMABLE NULL

It has been the common practice in NDE EC inspections to null the eddy current signal with the probe at the point of inspection however, in an automatic system this may cause problems. If, by chance, the probe is nulled while it is sensing a flaw, the dc level of the signal may be near the end of the linear range of the detection amplifiers (see Figure 5). In this case, a large flaw signal may lead to a saturation of the amplifier. Because both high pass and low pass filters are often used, and the EC instrument being used has the filter electronics after the nulling electronics, saturation causes the signal to appear as a zero level signal. Thus, in a worst case, the flaw would not be detected. In the case of a bad null during a manual inspection, the human operator seeing a saturated signal, would re-null and repeat the inspection. In the automatic system the easiest way to overcome this problem has been to implement a programmable null circuit into the EC instrument. This allows the storage of a null value, possibly obtained at a calibration block, for use at the inspection site. Another option is that a null value can be calculated from a waveform, possibly obtained at the inspection site, and then entered into the EC instrument via the programmable null. The development of a programmable null allows the automatic system to avoid bad nulls thus increasing the reliability of the inspection.

ADAPTIVE SCANNING

Manufacturing tolerances combined with the adverse conditions inside a gas turbine engine yield engine parts with a variety of dimensional differences. For example, holes may be unevenly spaced, web surfaces may be slightly warped or manufactured with differing thicknesses, and surfaces may be removed (or added to) in reworking. Several techniques have been developed to allow the automatic inspection process to accommodate the variations in geometries seen from part to part. Some of the techniques are hardware in design and some are software in design. At the present the three main techniques used are hole centering, the use of compliant surface probes, and air bearing probes.

The details of the hole centering algorithm have already been published (1). To summarize, the algorithm allows a probe to be centered over a hole to within 0.0005 inches even if the initial probe position is one probe diameter away from the hole. The process is fast and iterative, making successively more accurate movements towards center. One major change in the algorithm from reference (1) is that the one-time calibration to determine probe-to-machine coordinates and scaling factors is accomplished every time the probe is calibrated. This allows different probes of a given size and function to be used interchangeably with a given scan plan.
FIGURE 5. A) RAW EC Signal. Nulling occurs when the signal is at a peak. B) EC signal after the nulling but before the filters. C) Filtered EC Signal. The saturation appears as a dc response thus reducing the negative peak.
Tests have shown that large surface areas, such as webs, can be warped and additionally, the manufacturing tolerances can be large. During scanning with EC small variations in the liftoff distance can produce large signals. While the dimensioning algorithms will detect the severely distorted parts some surface variation must be tolerated to prevent rejecting many parts. At present, two hardware techniques, compliant contact probes and air bearing probes, have been developed to accommodate these variations. The contact surface probes are designed with a flexible spring connecting the coil housing to the probe body. The scan plan is written so that the spring is compressed halfway for the "average" part. Thus, surfaces of different parts can vary by one half of the range of the spring movement. A typical range is 0.030 inches allowing a part-to-part surface variation of 0.015 inches. Additionally, these probes have an alumina impregnated epoxy contact surface to prevent excessive wear of the probe surface.

The air bearing probes also incorporate a flexible spring but have the added feature of two small air holes that provide an air bearing for the coil to ride on. The flowing air actually draws the coil to within approximately 0.001 inch of the surface of the part. The spring acts to counter balance the air. Tests on these probes have shown that the liftoff distance is held at 0.001 +/- 0.0001 inches over a varying surface.

These three techniques, hole centering, compliant contact probes, and air bearing probes, should allow accommodation of most of the variations occurring in the engine parts while maintaining the reliability of the inspections. In UT the adaptive scanning is not critical as in EC because the squirter is positioned approximately 0.25 inches from the part. Variations in the part geometries can be accommodated by allowing a slightly wider time gate in the UT signal detection.

ALGORITHM PORTABILITY

In a manual of semi-automatic inspection the human adapts the physical movements of the inspection apparatus to the inspection of the part. Variations due to different apparatus, fixtureing, etc. are easily accomplished. For automatic inspections several sets of scan plans could be written to fit each of the different inspection systems but this would be undesirable. To avoid developing and maintaining different scan plans, efforts have been made to preserve the portability of each scan plan. Additionally, these efforts have allowed the mechanical positions used in the scan plans to come directly from the engine part blueprints. To achieve scan plan portability an offset positioning block and algorithm has been developed that 1) lets the machine coordinates match the engine part coordinates and 2) allows a scan plan developed on one system be used on another system. The algorithm thus allows the mechanical positions to be read directly off the part blueprints. Basically, this algorithm allows the mechanical controller to offset each of its axes such that the origin is at the cent of the turntable. Additional software allows variances due to the different heights of the part fixture jaws and locations of the calibration blocks to be taken into account. All of the offsets are stored in initialization files in the IMC. When the system is powered up the offsets automatically are implemented. If a part of an inspection system is replaced (such as the EC scanner or UT squirter) new offsets are obtained by the offset positioning algorithm and stored in the initialization files.
CONCLUSION

The principle techniques used in the RFC automatic inspections have been presented. While some of the techniques are not uncommon in NDE, many have had to be modified to allow usage on an automatic system. Others, like the programmable null, part dimensioning, and adaptive scanning are unique to an automatic inspection.

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REFERENCE