REAL-TIME FIELD RADIOGRAPHY OF AN OPERATING JET ENGINE USING A PORTABLE LINEAR ACCELERATOR

by

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ABSTRACT

To answer critical engineering questions about internal structural deformation and clearance changes in all flight regimes, a portable linear accelerator has been combined with high resolution imaging and computer enhancement to create a new tool for aerospace propulsion engineers.

INTRODUCTION

PURPOSE OF THIS INSPECTION

The purpose of this inspection was to analyze the relative motion of certain sealing points between rotating and stationary components within a 5,500# thrust, high bypass gas turbine engine. This was done to look for corroborative data relating to certain engineering assumptions about the action of these points. It was hoped that the resolution obtainable would be sufficient to track the transient behavior including rate of change, evenness of motion and degree of overshoot or undershoot at the ends of travel.

HISTORICAL PERSPECTIVE

The first record of high energy radiography of operating gas turbine engines is of work done by Mr. Peter Stuart working at Rolls Royce Advanced Projects Department in Bristol, England. This work made use of both film and real-time imaging techniques. This technique was developed to analyze the internal clearances, both cold and running of a variety of gas turbine engines. Most of the measurements of static states were made using radiographic film techniques. Additional inspections were done of transient changes in component configuration and clearances during acceleration and deceleration modes with real-time techniques. The x-ray system chosen for this work was an RDL 8Mv linear accelerator with a nominal output of 1,500 Rmm.

This work attracted the interest of General Electric and Part & Whitney who set out to develop this inspection capability. General Electric chose the same type x-ray source as Rolls Royce, while Pratt and Whitney opted for a Varian 2000 system which delivered comparable output energy with a 2,000Rmm output.

Pratt & Whitney developed a unique film camera capable of sequential .5 second exposures of as many as 50 14x17” pieces of x-ray film. This system used roll film and a complicated transport and shuttering system. This was used to give better definition of high speed transient events. Eventually, new scintillating glass screens were developed and coupled to the newly available image isocon cameras. This system generated true real-time images which were then fed into image processing computers.

Both Pratt & Whitney continued their use of these radiographic techniques until the early 1980's when the practice gradually faded from use. The generally accepted reason was the high on-going cost of maintaining these facilities and the associated highly trained operating staff. These costs could not be justified by the total system use, typically only during new engine development. Rolls Royce has maintained a degree of real-time capability to the present day and G.E. has merged with Snecma where they also have an operating real-time complex.

EQUIPMENT

X-RAY SOURCE

The x-ray equipment used for this project was a Varian MINI-LINATRON 6Mv portable linear accelerator. The nominal output energy of this system is 6Mv with a rated x-ray flux of 800Rmm. This system consists of a stand-alone linear accelerator plumbed to an rf generating cabinet. This configuration allows the small x-ray source (15"L, 12"W, 14"H, 100lbs) to be easily positioned in confined spaces and supported by a simple support structure. In this case, small (6 ft x 2 ft) mobile scissors lifts were used to support the source and the imaging system. The rf generator is a 300lb cabinet which was placed at the base of the scissors lift. Microwave energy was fed to the accelerator via sections of flexible waveguide. The rf generator was powered remotely from the modulator cabinet distanced from the inspection site by 250 ft of cabling. This unit supplies all drive, control and interlock circuitry and is driven from a.c. line power. The control console consisted of a 5 lb unit cabled to the modulator and placed within the motor control room. An additional remote safety box was attached to the rf cabinet at the x-ray generating site. This unit contains a prewarning horn and flashing light, as well as a system enable/disable key, an emergency off push-button switch. All of these features are similar in function to standard safety controls and warning systems common to fixed radiation facilities. Heat generating components are cooled by means of a portable water conditioner located adjacent to the modulator.

IMAGER

The primary imager was a 6/9 Image Intensifier. Two fields of view (6"& 9") were remotely selectable during the course of the inspection. Coupled to the output of the intensifier was a high resolution vidicon type video camera. The output of the camera was fed in RS170 video format to the primary video monitor located in the control room. The raw data was also captured directly on an SVHS recorder for later detailed processing at the AlliedSignal computer facility at the main plant in Phoenix. The real-time image was fed through a stand alone Pentium based image processor in the control room. This made possible real-time analysis and clarification the live image which in turn led to more exact placement and adjustment of the overall system.

SETUP

GENERAL

The system was transported to the site for it's base in California in a small van containing all primary system components, as well as auxiliary support equipment.

Figure 1 shows the overall plan view of the AlliedSignal San Tan Test facility. The location is south of Chandler, AZ. As noted, the nearest habitation was over 1/2 mile from the main gate. The x-ray system was oriented to project the primary beam into open desert to the west.
Figure 2 shows the location of the motor test area in relation to the other operational areas of the facility. The motor was set-up at a remote acoustic test stand, which greatly simplified the establishment of the radiation perimeter.

Figure 3 details the relationships of the various components placed with the motor. The RF cabinet, along with the accelerator, were rolled across the tarmac to the engine test stand and cabled to the modulator, which was located alongside the motor control room (approximately 225 ft distance). The control console and image acquisition system were set up in the control room near the operator's station. System was operational and ready for test of the proposed safety perimeter and certification of the Arizona Radiation Authorities in two hours.
Figure 4 lays out the general location of the eventual 2 mR radiation perimeter.

RADIATION PERIMETER

Of primary concern in any work with a linear accelerator outside of the normal shielded and carefully controlled facility is the establishment of a safe, controllable radiation perimeter. This must, in most cases, define a 2mR/hr border to the inspection area that is defendable against intrusion by a combination of direct observation and physical barriers. An initial analysis of the area had suggested using the facility fences combined with radiographic warning ribbon to define the limit behind the source. After a careful search of all areas within the intended perimeter had assured that all personnel where clear, a radio equipped observer was stationed on the nearby hill. From this vantage point the entire area was kept under constant surveillance. Any intrusions could be safely noted and the x-ray system operator, also on the radio net, could terminate x-ray production in time to assure no one could enter a radiation field.

The verification of the perimeter was done by gradually bringing the x-ray system up to the output needed to generate acceptable images while monitoring the levels around the border. If any readings had exceeded the 2mR limit, adjustments would have been made to include a larger area at that location until all radiation levels were within tolerances.

SOURCE

The 100 lb. linear accelerator was mounted on a small motorized scissors lift which was positioned along side the left side of the motor. This device allowed the source position to be adjusted horizontally and vertically in reference to areas of interest within the motor. The R.F. cabinet was placed on the tarmac next to the lift and coupled to the accelerator. The R.F. cabinet is responsible for generating the intense microwave energy required to drive the accelerator. This energy is piped to the source via flexible waveguide. This flexibility allows easy adjustment of the source position. In this case, a total of two ten foot sections were required for full range of motion. The accelerator is fitted with a basic tungsten collimator that limits the projected beam to a 30(included cone. This was directed through the motor below the centerline. During the course of the inspection sessions the beam was shifted horizontally and vertically along the motor, taking care to maintain an orientation perpendicular to the rotational centerline. This was checked with a portable 4mW diode laser which clips to the output end of the collimator during set-up and is then removed during exposures.

IMAGER

The image intensifier was mounted on an identical scissors lift along the right side of the motor. The initial position relative to the source was established by measurement. Final detailed positioning of the source and imager was done using actual live x-ray images as reference points.

THE INSPECTION

AREAS OF INTEREST

Each of the areas of interest within the motor react in a unique manner to different motor power settings as well as the manner and order in which these settings and applied. For this reason, a separate flight profile was developed for each point. These included operations at ground and flight idle settings interspersed with power levels up to maximum climb power. Power changes were made at rates similar to those normally experienced in civilian air travel as well as sharp "snap" changes. These latter generate the greatest stresses and relative motions between the rotating and non-rotating sections of the engine. It is the relationship of the clearances between these sections that determines the safety and efficiency of a turbine engine. Hot, compressed gases flowing through the motor must be contained with a minimum bypass between the rotor blades and static structure. The high rotation rates (30 to 50 thousand rpm) do not allow the actual physical contact such as is possible at the piston ring to cylinder wall of an internal combustion engine. Clearly the engineering challenges of sealing this type of motor are considerable. All of the same dimensional changes associated with bringing a motor up to full operating temperature experienced within an internal combustion engine must be accounted for in a gas turbine. Additionally, since the weight of the overall unit is very important for a flight motor, the non-rotating structure must be as light as possible. This means that, unlike an internal combustion engine, there is a good deal of relative motion at the sealing points. Every effort is made to assure that this motion will be along the centerline of the motor. The rotating half of the seals are typically very narrow knife edges in cross section while the static half has a flat linear cross section parallel to the centerline. This allows movement to take place along this boundary while still maintaining the needed clearance across the seal.

It was the motion of these sealing points that was important for this inspection. Attention was directed at the seal gap clearance at static power settings and during power transitions. This was to determine the amount of change, if any, in the gap caused by non-linear for and aft motion of the static sealing surface. The amount of total motion as well as the degree of overshoot past the stabilized positions at each power setting was also important. At some sealing points the design clearance between the seal components at full range of motion end points was such that only a small degree of overshoot could be tolerated. Exceeding these tolerances can cause direct physical contact with the rotating section with resulting scuffing and deterioration.

A TYPICAL INSPECTION ROUTINE

At certain stages during each inspection routine film cassettes where placed at the input surface of the image intensifier and exposed to record a high resolution image that can be used later for measurement reference as well as static state documentation. This was done before the start-up, after an initial ten minute warm-up period and at selected static power settings during the flight profile.

Real-time images were captured along with each of the film exposures, during all transitions between power settings and at selected static power settings.

Before engine start-up, the relative positions of the source and imager were fine tuned to optimize the alignment with the area of interest. This was done using live images to determine the necessary orientation required to minimize geometric distortion and clearly image the various gaps and clearances.

Once the system was properly positioned the motor was taken through each required flight profile. Images were not captured during the entire profile since there were many periods of static power settings during which temperatures and stresses were allowed to stabilize that did not require detailed analysis. Since the linear accelerator system is an electronic device, it was a simple matter to turn it off during those periods when it was not needed.

Before the initiation of x-rays for each inspection session, a careful sweep of the radiation area was made to be sure no personnel were remaining. The radiation safety officer (R.O.) then declared the area clear and authorized the x-ray system operator to begin x-ray generation. During those period within each flight profile when film was placed and exposed, the R.O. determined that the x-rays were off and led the radiographer into the area of the motor using a hand held radiation meter. The R.O. was at all times in direct radio contact with the x-ray system operator.

OBSERVATIONS AND CONCLUSIONS

This project was carried out in July of 1996 when daytime ambient temperatures at the San Tan Facility seldom fell below 110 (F and were recorded as high as 121(F. Despite these severe conditions all equipment functioned properly. Provisions were made to cover the source and imager with reflective blankets to reduce the load on the water cooling unit, which was able to maintain the constant 30(C required. No rain or wind blown dust was encountered during this work, however, the system has functioned in these conditions in the past with no interference. The timing of the work was adjusted to minimize the impact on the rest of the facility by working after the end of day shift and was completed in two days. During the course of the inspection no problems were encountered with radiation perimeter control.

Image quality and resolution were similar to that obtained at by the larger fixed facilities. This was accomplished at the fixed, one time cost for the project with none of the additional facility or personnel costs that have prevented the wider use of the technology in the past.