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# LASER-OPTICAL BLADE TIP CLEARANCE MEASUREMENT SYSTEM

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# LASER-OPTICAL BLADE TIP CLEARANCE MEASUREMENT SYSTEM

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## ABSTRACT

The need for blade tip clearance instrumentation has been intensified recently by advances in technology of gas turbine engines. A new laser-optical measurement system has been developed to measure single blade tip clearances and average blade tip clearances between a rotor and its gas path seal in rotating component rigs and complete engines. The system is applicable to fan, compressor and turbine blade tip clearance measurements. The engine mounted probe is particularly suitable for operation in the extreme turbine environment. The measurement system consists of an optical subsystem, an electronic subsystem and a computing and graphic terminal. Bench tests and environmental tests were conducted to confirm operation at temperatures, pressures, and vibration levels typically encountered in an operating gas turbine engine.

## INTRODUCTION

The need for blade tip clearance instrumentation has been intensified recently by advances in technology of gas turbine engines. Improved engine designs encompass lightweight high-performance concepts such as small thin airfoils for blades. Excess clearance allows a portion of the engine gas to flow over the blade tip without performing useful work. Moreover, insufficient blade tip clearance may cause interference which can jeopardize the engine integrity.

Previously, it had been possible to measure average blade tip clearance over several rotor revolutions, but the system (1) did not have adequate response for transient or single blade tip clearance measurements. The Pratt & Whitney Aircraft Group, Government Products Division, designed and fabricated, under contract to NASA Lewis, a system that possessed adequate time response and that was capable of measuring and displaying single as well as average blade clearances.

This new laser-optical measurement system (2) was designed to measure single blade tip clearances and average blade tip clearances between a rotor and its gas path seal in rotating component rigs and complete engines. The system is applicable to fan, compressor, and turbine blade tip clearance measurements. The engine mounted probe is particularly suitable for operation in the extreme turbine environment.

The measurement system has been bench tested using typical rotor blades up to simulated rotor speeds of 60 000 rpm, blade tip speeds of 610 m/sec (2000 ft/sec) and blade tip thicknesses as small as 0.79 mm (0.031 in.). These tests showed that the system has an overall clearance measurement range of 0 to 3.05 mm (0.120 in.). Computed two-sigma values based on the best fit calibration curve for the system showed a deviation from best fit of less than 0.025 mm (1 mil), a resolution of less than 0.025 mm (1 mil) and a repeatability of less than 0.05 mm (2 mil).

Environmental tests were also conducted to confirm probe operation at adjacent wall temperatures up to 1300 K (1900° F), gas path operating pressures up to 30 atmospheres, and vibration levels typically encountered in an operating gas turbine engine. Results indicate no degradation in system performance beyond the previously stated bench test data.

The measurement system consists of an optical subsystem, an electronic subsystem and a computing and graphic thermal. The optical subsystem includes an optical probe, fiber optic cables and an environmental enclosure containing the electro-optical components. The electronic subsystem chassis provides the scan, gate and process functions required for single and average blade clearance measurements. Optical and electronic subsystem control and data presentations are provided by the computing and graphic display terminal. Software programs present data as a plot of clearance versus time or clearance versus blade number.

## SYSTEM DESCRIPTION

The measurement system consists of an optical subsystem, and electronic subsystem and a computing and graphic terminal. Figure 1 illustrates the overall system configuration.

### Optical Subsystem

The optical subsystem includes an optical probe, fiber optic cables and an environmental enclosure containing the electro-optical components. A schematic of the basic probe optical system is shown in Fig. 2. The light source is imaged on the target blade tip through a lens and a saphire prism. The reflected light returns through the prism and lens and is focused on the output coherent fiber optic bundle. The radial movement of the blade tip from A to B corresponds to the movement of the light spot from A' to B' on the output bundle. The tip clearance is measured relative to the shroud surface by correcting for the fixed zero offset distance between the prism face and the shroud surface. The prism folds the optical path allowing the use of a single probe housing for both the input and output optics. Probe cooling is achieved with dry nitrogen flowing along the inner wall of the probe housing. The prism is spaced away 0.5 mm from the viewing slot at the end of the housing. The nitrogen flow passes across the prism and exits through the slot, thereby keeping the prism face clean. Figure 3 is a photograph of the probe showing the braided stainless steel sheathed optical cables. The probe tip is designed to bayonet fit directly to the shroud. Errors in the zero offset distance induced by thermal growth are minimized by keeping the distance from the bayonet mount to the shroud surface as short as possible. Note the viewing slot at the tip of the probe.

The environmental enclosure which contains the electro-optical components is connected to the probe by two coherent fiber optic cable bundles 2.74 meters in length. The 10 mW helium-neon laser light source

(632.8 nm wavelength) is coupled to the input fiber bundle through a lens assembly (Fig. 1). The lens assembly includes a 20 power microscope objective lens to focus the laser beam down to a single fiber of approximately 10 micrometers in diameter. A graded neutral-density filter wheel located between the laser and the objective lens is used to control the intensity at the fiber. This control is necessary to adjust for the variation in the optical properties of engine blades. Moreover, control is also required to adjust the energy received by the image processing system at different engine speeds and system operating modes.

The output fiber bundle is coupled to the image intensifier through a relay lens assembly and an image intensifier lens. The relay lens assembly serves three purposes: (1) to receive and collimate the laser spot image received from the probe output bundle, (2) to filter unwanted background radiation by using a laser line band-pass filter, and (3) to collect and detect peripheral radiation from the probe output which is not collected by the relay lens and utilize the energy to produce a blade passing pulse train.

The objective lens of the relay lens assembly views the probe output spot image through a hole in the center of a concave mirror. Approximately 70% of the fiber optic bundle output intensity is received by the objective lens while the annular mirror segment collects the peripheral radiation from the bundle which would otherwise be lost. This peripheral radiation is focused onto the tip of a fiber optic light guide and is transmitted to a photomultiplier tube (PMT). As the blades pass by the probe, the photomultiplier tube detects the light pulses and generates a blade passing pulse train.

The collimated and filtered signal radiation from the objective lens is reimaged onto the image intensifier faceplate by the image intensifier lens. The lens aperture is controlled by a motorized iris. The light level at the image intensifier faceplate is thus regulated by both the iris size and by the neutral density filter at the laser output. Moreover, during conditions of sufficient signal radiation, system resolution is enhanced by reducing the size of the iris to a minimum.

The image intensifier is a novel proximity focused microchannel plate type coupled to a linear photodiode array (LPA). The tube is made up of an input window with an S20 photocathode deposited on the inside surface, a microchannel plate, and an output phosphor screen coupled directly to the LPA by way of a fiber optic faceplate. The array consists of 256 photodiodes each 0.025 mm (1 mil) wide by 0.43 mm (17 mil) long and spaced 0.025 mm (1 mil) center to center. The microchannel plate is an array of 12 μm diameter channels fused together into the shape of a thin plate. By applying a voltage across the faces of the plate, electron gain is achieved through secondary emission within each microchannel. The overall light gain is in the range of 1000 to 10 000. The image intensification process is performed internally with no external electronics other than a gateable power supply. The tube is 40 mm in diameter and 30 mm long.

The LPA signal conditioner (Fig. 1) consists of an amplifier and a line driver.

Electronic Subsystem

The electronic subsystem controls the components of the optical subsystem and processes the signal from the LPA signal conditioner. It also intefaces with the computing and graphic terminal by accepting commands and transmitting tip clearance data. The system operating mode is determined by the operator through the keyboard of the terminal. The system software resident in the terminal transforms the operator's request into the appropriate command sequence for transmission to the electronic subsystem. The operator can select any of the following operating modes: (1) AVERAGE Mode which is the optical average of all the blades taken each revolution, (2) SINGLE BLADE Mode 1 which is a sequence of selected blades taken one at a time where each blade is averaged over a selected number of revolutions, and (3) SINGLE BLADE Mode 2 which is a sequence of measurements of a single selected blade where each measurement is averaged over a selected number of revolutions. If either of the SINGLE BLADE modes is selected the operator also provides BLADE NUMBER and NUMBER OF REVOLUTIONS information. The BLADE NUMBER, in the range 1 to 120, is the sequence of blade numbers for SINGLE BLADE Mode 1 or the blade number for SINGLE BLADE Mode 2. The NUMBER OF REVOLUTIONS, in the range 1 to 255, is the number of rotor revolutions that will be optically averaged in the SINGLE BLADE modes. This feature is provided so that the operator may increase the average light level if insufficient radiation is available for proper signal conditioning. In all modes the operator selects a minimum and maximum clearance. When the software has detected a measured clearance at or less than the preselected minimum the MINIMUM CLEARANCE ALARM is activated. When the software has detected a measured clearance at or greater that the preselected maximum the MAXIMUM CLEARANCE ALARM is activated. The clearance alarms illuminate front panel alarm indicators on the electronic subsystem.

The electronic subsystem executes the commands from the terminal by sending gate and scan control signals to the image intensifier and the PLA (Fig. 1). In the AVERAGE Mode the image intensifier is gated on continuously and the LPA optically averages the clearance of all the blades. In the SINGLE BLADE modes the image intensifier is gated on to view only the requested BLADE NUMBER. The LPA optically averages the clearance for the chosen NUMBER OF REVOLUTIONS. In all modes the video processor and clearance detector (Fig. 1) convert the diode site number with the greatest light level to clearance information. A preselected zero offset feature corrects for the zero offset distance between the probe prism face and the shroud surface (Fig. 2). Thus all clearance data is measured relative to the shroud surface. The video processor also generates an automatic gain control (AGC) voltage to optimize the LPA output. In addition, any detected hardware error in the electronic subsystem generates an error message which is transmitted to the terminal indicating that the data are invalid.

In the blade and index counter, a once-per-rotor-revolution index pulse is used in combination with the blade passing pulse train from the PMT to generate synchronization signals corresponding to the selected BLADE NUMBER. For the infrequent condition where there is insufficient radiation to be detected by the PMT, an externally provided synthesized blade passing pulse train may be substituted.

The General Purpose Inteface Bus (IEEE STD 488-1975) is the interface system which connects the electronic subsystem and the computing and graphic terminal. Figure 4 is a photograph of the system hardware with all of the major components labeled. The 30 meter (100 ft) interconnecting cable connects the optical and electronic subsystems.

System Displays

The computing and graphic terminal controls the electronics subsystem and provides clearance data presentations. Keyboard entries of test conditions are accepted by programs resident in the terminal core memory. Upon execution, the programs issue control instructions and receive blade tip clearance data in return via the interface. In the AVERAGE Mode, data are presented on the graphic terminal screen in a plot of clearance in mils versus scan # (scan number). This display is illustrated in Fig. 5. The abscissa or scan # axis is similar to a time axis since each scan represents a time equal to approximately the period of one revolution times the NUMBER OF REVOLUTIONS. The average of all the scans is indicated as AVG. The maximum and minimum clearances are shown as MAX and MIN, respectively. Figure 6 is the display of the SINGLE BLADE Mode 1 where data are presented as clearance in mils versus blade # (blade number). The SINGLE BLADE Mode 2 data are presented in a plot of clearance in mils versus scan #. This display is shown in Fig. 7 where again the scan # axis is similar to a time axis. A zoom capability is provided which allows the operator to expand both axes of any plot.

## PERFORMANCE

Bench tests were conducted to determine the measurement system's operational performance characteristics. Both static calibration and dynamic performance were evaluated. Further, the measurement system probe was subjected to environmental conditions typically encountered in an operating gas turbine engine.

### Bench Tests

A static calibration was performed with the system probe mounted in a micrometer calibration fixture. Calibration range was from zero to 3.28 mm (129 mil). The distance was measured from probe tip to micrometer face and the increment was one diode site. Each calibration point was set by rotating the micrometer to obtain one diode increment change. The calibration points were plotted as diode site versus micrometer reading. The data were fit to a third order polynomial equation using a least squares deviation method. Two-sigma values show a deviation from best fit of less than 0.025 mm (1 mil).

An upper limit on measurement system resolution was also obtained from the calibration data. Since the system has a nonlinear characteristic, the change in displacement corresponding to one diode site is not uniform. The maximum observed incremental change between diode sites was less than 0.076 mm (3 mil), but 97% of the changes were less than 0.05 mm (2 mil). The incremental change for one diode site is twice the resolution since a deviation in displacement equivalent to greater than one half diode site would cause the adjacent site to indicate. Thus the two-sigma value of resolution is less than 0.025 mm (1 mil).

Repeatability data were also recorded for two cycles over the calibration range in increments of 25 diode sites upscale and downscale. Displacements calculated from the diode site using the third order polynomial equation derived previously were compared to measured displacements. The maximum deviation or repeatability was less than 0.05 mm (2 mil).

Dynamic performance of the measurement system was accomplished by using a laboratory simulation of a rotating blade row. An acousto-optic modulator was used to interrupt the laser beam thus producing pulses of light equivalent to a rotating blade row. Rotor speeds up to 60 000 rpm, blade tip speeds up to 610 m/sec (2000 ft/sec) and blade tip thicknesses down to 0.79 mm (0.031 in.) were simulated. The targets were six blades, two fan, two compressor, and two turbine, all taken out of service with long operating exposure. The clearance was set to 1.27 mm (50.0 mil). The NUMBER OF REVOLUTIONS was increased until there was sufficient reflected light for proper signal conditioning. Results of the dynamic tests indicate that no more than 100 revolutions per scan would be required in the worst case and less than 10 in most cases.

### Environmental Tests

The environmental evaluation tests subjected the measurement system probe to temperature, pressure, and vibration environments typically encountered in an operating gas turbine engine. The temperature test evaluated the measurment system performance with the probe mounted in a configuration similar to that used in an actual gas turbine installation where adjacent wall temperatures vary from near ambient to 1300 K (1900° F). The test rig basically consisted of a 50 mm diameter stainless steel pipe, 150 mm in length, and support hardware. One end of the pipe was inserted into a variable temperature furnace which provided the heat source. At the other end of the pipe, the probe was inserted perpendicular to the pipe axis and through the pipe wall such that the probe tip was flush with the pipe inner wall, thus providing the simulated installation. A hole was provided through the pipe wall opposite the probe to allow for micrometer access. A thermocouple was attached to the pipe inner wall approximately 35 mm from the probe tip center and toward the heat source. The probe was cooled by gaseous nitrogen.

Data were obtained with simulated wall temperatures from approximately 367 to 1300 K. At each temperature a gap of 1.27 mm (50.0 mil) was established by adjusting the micrometer to obtain a zero gap and then adjusting the micrometer to obtain the proper displacement. This procedure minimized any potential errors induced by thermal growth of the test rig.

For the pressure and vibration test, a fixed clearance target adapter was coupled to the probe tip and adjusted to 1.27 mm (50.0 mil). The probe body was then inserted into a pressurization adapter which allowed the probe assembly to be subjected to elevated pressure via the slot opening at the probe tip. In 1 atmosphere increments, the probe was pressurized with gaseous nitrogen from ambient to 30 atmospheres. The measurement system data were taken at each pressure setting. For the vibration test, the probe body was attached to a vibration test shaker by adapter fixtures. These fixtures allowed the probe to be excited along three mutually perpendicular axes, one axis at a time. Along each axis, the probe was subjected to a constant 12.7 mm/sec velocity excitation sweep from 50 to 2500 Hz of approximately 10 minutes duration. Data were obtained during each excitation sweep.

The environmental evaluation tests were designed to test the repeatability of the system under each environmental condition. The repeatability of each test was well within the measurement made during the static calibration, that is, 0.05 mm (2 mil).

## CONCLUDING REMARKS

A laser-optical measurement system has been described which is designed to measure single blade tip clearances and average blade tip clearances between a rotor and its gas path seal in rotary component rigs and complete engines. The system has a number of innovative features that combine optical, electro-optical, electronic and computer/graphic elements. It is widely applicable for the measurement and display of average and single blade tip clearances in operating rotating machinery over a full range of rotational speeds and a wide variety of blade materials and configurations.

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2. Ford, M. J., et. al., "Advanced Optical Blade Tip Clearance Measurement System," FR-10200A, Pratt and Whitney Aircraft Group, West Palm Beach, Fla., 1978. NASA CR-159402, 1978.

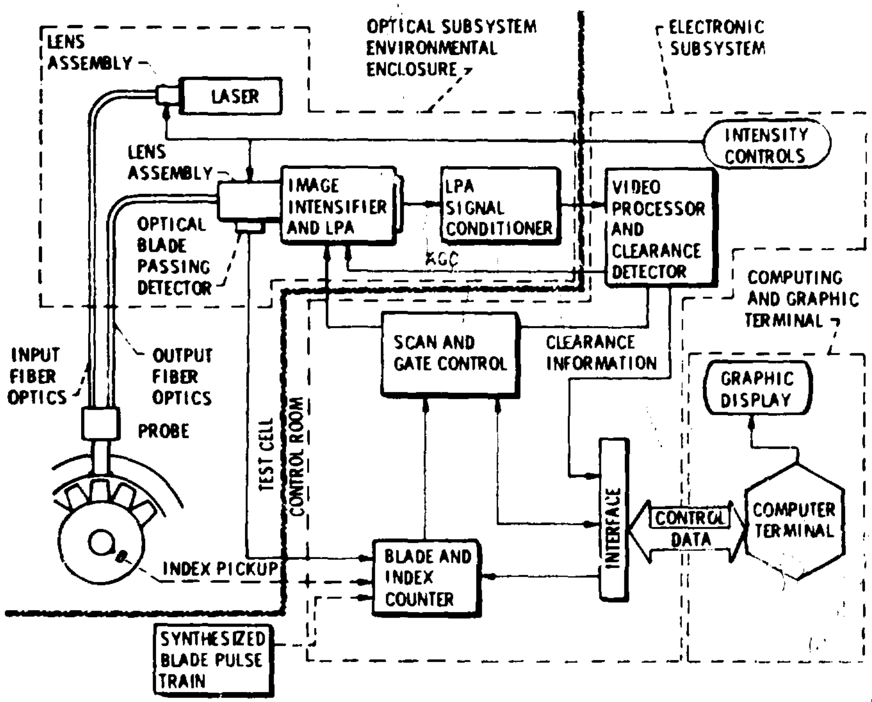


Figure 1. - Overall system configuration.

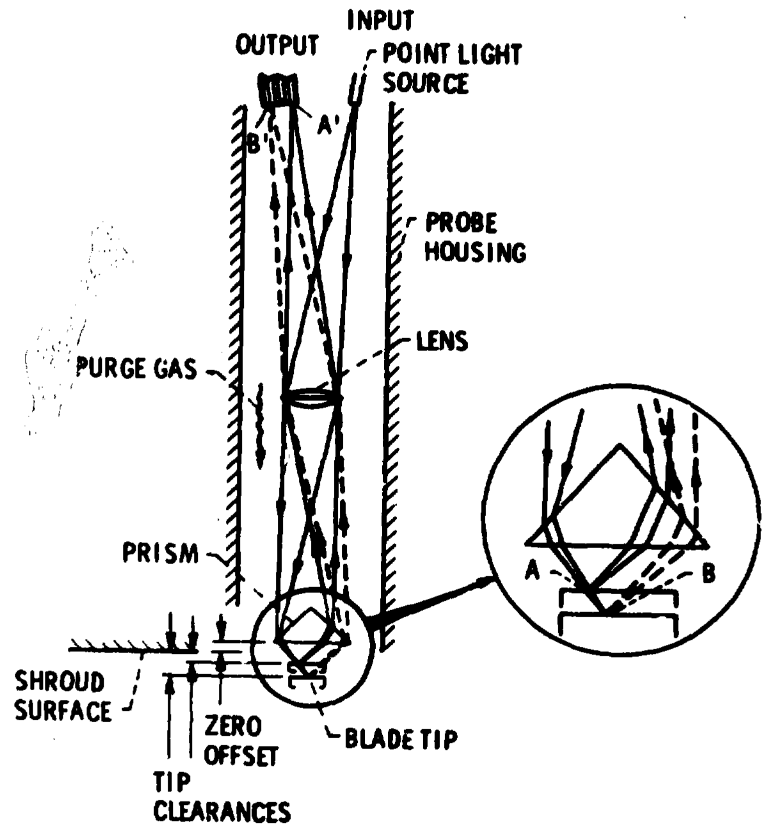


Figure 2. - Basic probe optical system.

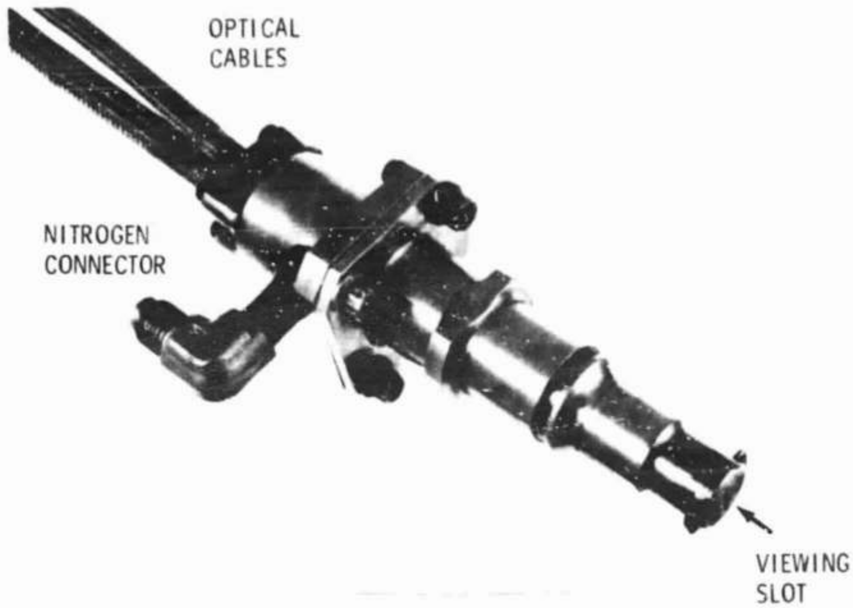


Figure 3. - Photograph of probe showing optical cables.

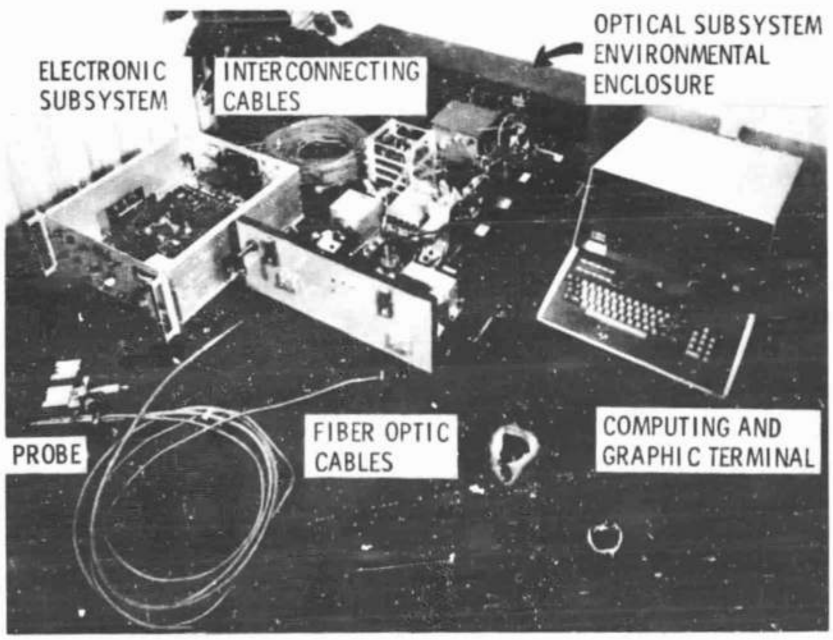


Figure 4. - Photograph of system components.

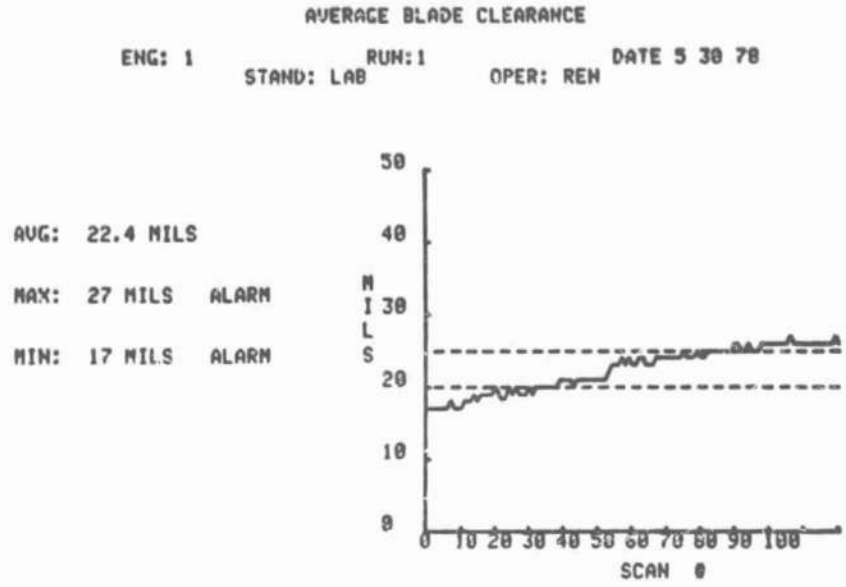


Figure 5. - Graphic terminal display of average blade clearance vs. scan number.

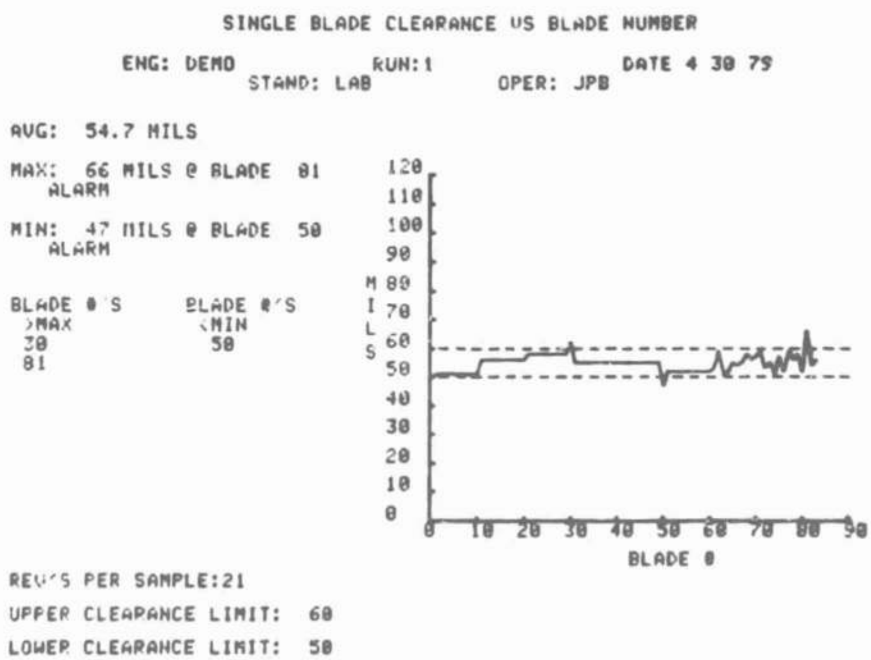


Figure 6. - Graphic terminal display of single blade clearance vs. blade number.

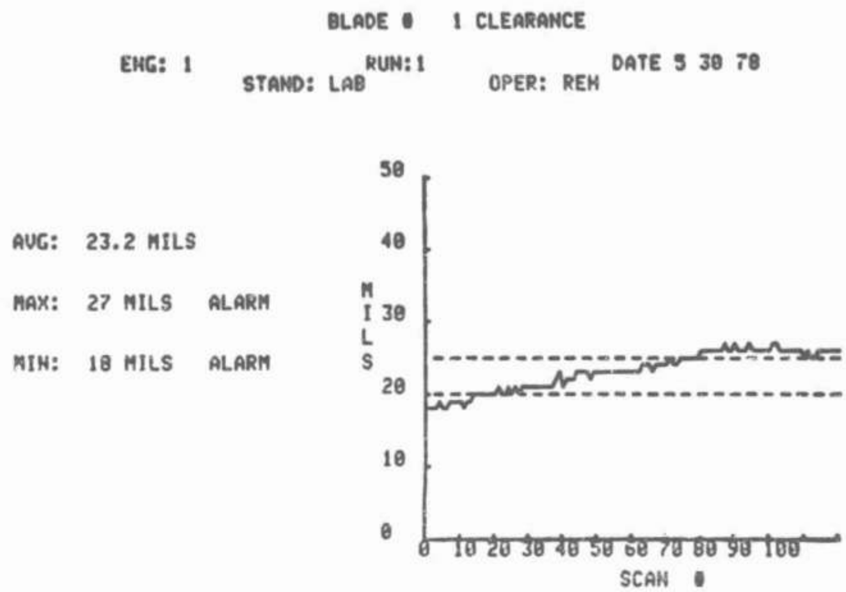


Figure 7. - Graphic terminal display of single blade clearance vs. scan number.