(NASA-CR-159434) ANALYSIS AND PRELIMINARY DESIGN OF AN OPTICAL DIGITAL TIP CLEARANCE SENSOR FOR PROPULSION CONTROL (General Electric Co.) 28 p HC A03/MF A01 CSCL 21E
N79-15053
Unclas
G3/07 43208

NASA CR-159434

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ANALYSIS AND PRELIMINARY DESIGN OF AN OPTICAL DIGITAL TIP CLEARANCE SENSOR FOP PROPULSION CONTROL

by G. L. Poppel

GENERAL ELECTRIC COMPANY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
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SUMMARY

The objective of this program was to identify innovative, promising concepts for passive, digital-compatible optical sensors, and to establish the technology base required for their development. The intended application for these sensors is in digital electronic propulsion control systems for commercial and military aircraft. The program was divided into three specific work tasks as described below.

Task 1 was an idea generating phase in which a screening study was performed to identify and evaluate several promising concepts, from which one would be chosen to pursue through the rest of the program. Sensors to measure such parameters as air temperature, air pressure, air density, flow velocity, and tip clearance were presented. The optical digital tip clearance sensor was chosen as most promising.

Task 2 consisted of the analysis and preliminary design of the tip clearance sensor selected in Task 1. Application was chosen to be in the TF34 compressor section. Laboratory experiments were performed to investigate several aspects of the sensor's optical circuit. Assessments were made of each sensor subsystem and recommendations were given for necessary development programs. Quantitative predictions were made of such performance goals as sensor range, accuracy, transient response, environmental sensitivity and power requirements.

Task 3 consisted of the preparation of a test plan for demonstrating the feasibility of the concept. A demonstration was planned to include all elements of the sensor in a brassboard model. Through recorded measurements, the test was designed to show that tip clearance can accurately be measured and that ultimate performance goals can be met.

INTRODUCTION

The need for Optical Digital Sensor Technology development programs relates fundamentally to the increased complexity of the next generation of propulsion systems, in terms of the number of controlled variables, inherent cycle variability, inlet-engine-exhaust control integration, and engine condition monitoring. This level of engine complexity and the expanding need for more complete aircraft/engine control integration, forces a commensurate increase in the complexity and capability of the control system, which includes sensor technology.

Digital electronics represents the only viable means of achieving the desired reliability, life cycle cost, and weight for control systems applied to advanced gas turbine engines. With the inherent ability to "time share" in the computations section of the control, increasing control complexity yields a very much smaller increase in hardware (and hence failure rates), when compared to present control system mechanizations. Digital electronic approaches also offer improved accuracy with environmental tolerances when compared to analog approaches.

Aircraft gas turbine performance and efficiency are severely affected by compressor and turbine blade tip clearances. It has been shown on development engines that efficiency can be improved at steady-state power levels by judiciously cooling the stator section. Mechanical methods can also be devised to vary the stator diameter. Future engines could be made more efficient at varied power levels by a closed-loop control and actuation system that would automatically maintain the desired running clearance. A necessary element of this system would be a tip clearance sensor that is simple and reliable. Optical sensing methods, which are non contacting and do not need a servo pressure source, have obvious advantages over mechanical methods. An optical tip clearance sensor would be suitable for tip clearance measurement/control throughout the gas turbine industry.

SENSOR CONCEPT SCREENING STUDY

CONCEPT GENERATION

An idea generating study was conducted to help identify promising concepts for passive, digital compatible optical sensors. Several literature searches were performed based on investigating the following three topics:

(1) Optical or electro-optical devices and phenomena and their applicability to possible sensor systems.

(2) Available theory and data on the variation of optical properties of materials as a function of pressure, temperature, and strain.

(3) Methods for detecting changes in optical properties.

The literature searches served not only to stimulate sensor ideas directly, but also to broaden the general optics technology base.

IDENTIFIED CONCEPTS AND EVALUATION

The following is a list of the twelve optical sensor concepts generated during the screening study. Detail descriptions are contained in the Task 1 Concept Screening Study Final Report.

(1) Refractive Index Temperature Sensor
(2) Temperature/Pressure Encoder
(3) Turbine Tip Clearance Sensor
(4) Vortex Shedding Flow Sensor/Velocimeter
(5) Vortex Shedding Flow Sensor;Reflective
(6) Temperature/Pressure Sensor By Triangulation
(7) Turbine Inlet Temperature By Emission
(8) Fuel Drop Size Monitor
(9) Activated Gas Fragment Velocimeter
(10) Velocimeter By Cross-Correlation
(11) Air Temperature By Absorption

The Contractor rated the concepts under the categories of degree of digital compatibility, ease of development, engine/control system payoff, and on-engine feasibility. These ratings reflected a maximum feasibility confidence and payoff significance towards the turbine tip clearance sensor.

CONCLUSIONS

It was concluded that the turbine tip clearance sensor concept promised the most payoff for the least risk and should be developed further. An engine mounted tip clearance sensor would contribute to a significant improvement in engine efficiency from operating at small tip clearances by allowing closed loop clearance control. Decreased specific fuel consumption and other environmental factors increase the importance of developing this sensor. It was decided by the NASA Project Manager to pursue this concept through the remainder of the Contract.

PRELIMINARY DESIGN AND ANALYSIS OF THE OPTICAL TIP CLEARANCE SENSOR

SENSOR PROFILE

The basic sensing concept employed by this optical tip clearance sensor is shown in Figure 1. It consists of bringing light from a source through fiber optic cables, and projecting it across the engine rotor cavity as a very narrow beam. The thin beam is produced by projecting the image of the tip of the input fiber optic cable to the center of the sensing region using an input lens of correct focal length and a beam narrowing aperture. The ray of light then forms a chord across the arc swept by the tip of the rotor blades. As the blades rotate, the light ray is periodically interrupted. Beam thinness affects the abruptness of the light attenuation and thus inherent sensor accuracy. A focusing output lens concentrates the signal into the output fiber optic cable which activates a photodiode. The clearance can be determined by measuring the duration of time that the signal is blocked and unblocked by counting digital clock pulses. The ratio of these counts is an indication of clearance, that is, the longer the signal is blocked at a given speed, the closer the tip is to the shroud.

Sensor geometrical relationships are presented in Figure 2. Variable definitions are as follows:

- R - Rotor blade radius, mm
- N - Rotor speed, rpm
- α - (θ max) - Angle between blades, rad
- θ - Angle of light blockage, rad
- t_1 - Time of light blockage, seconds
- t_2 - Time of blade passing, seconds
- δ - Tip clearance, mm

The derived equation for calculating tip clearance is,

$$\delta = \frac{R \cos \left(\alpha t_1/2t_2\right)}{\sin \phi} - R$$

As each successive rotor blade blocks and unblocks the light beam, a point is reached as clearance decreases, when the next blade enters the sensing region before the previous blade has left. The radial distance between when a blade first begins to nip the light beam and when this point is reached, is the sensor's useable range of measurement. This range varies with the diametral size and blade spacing of each particular rotor to which the sensor is applied, according to the equation,

$$\text{Sensor Range} = R\left[1-\cos\left(\alpha/2\right)\right]$$

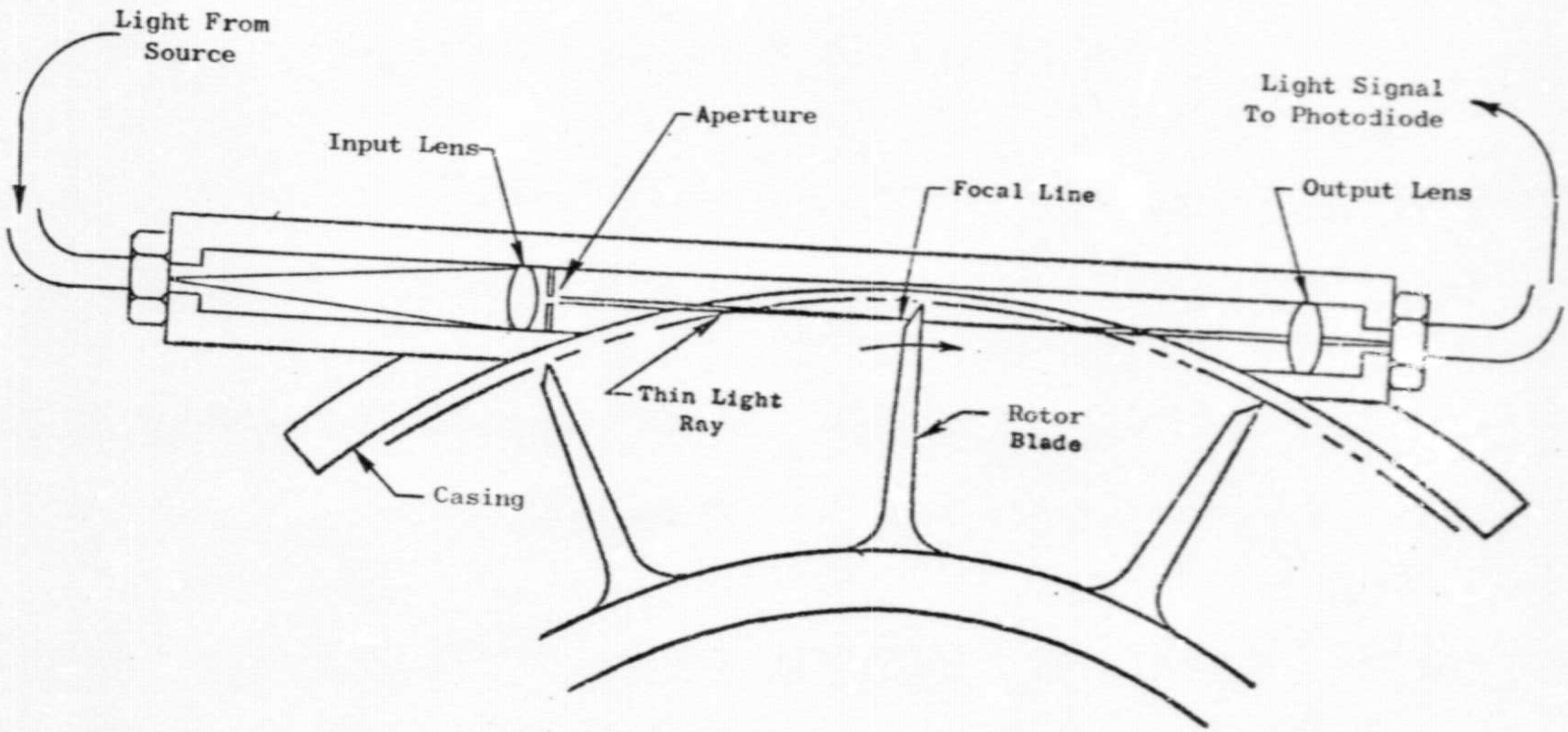
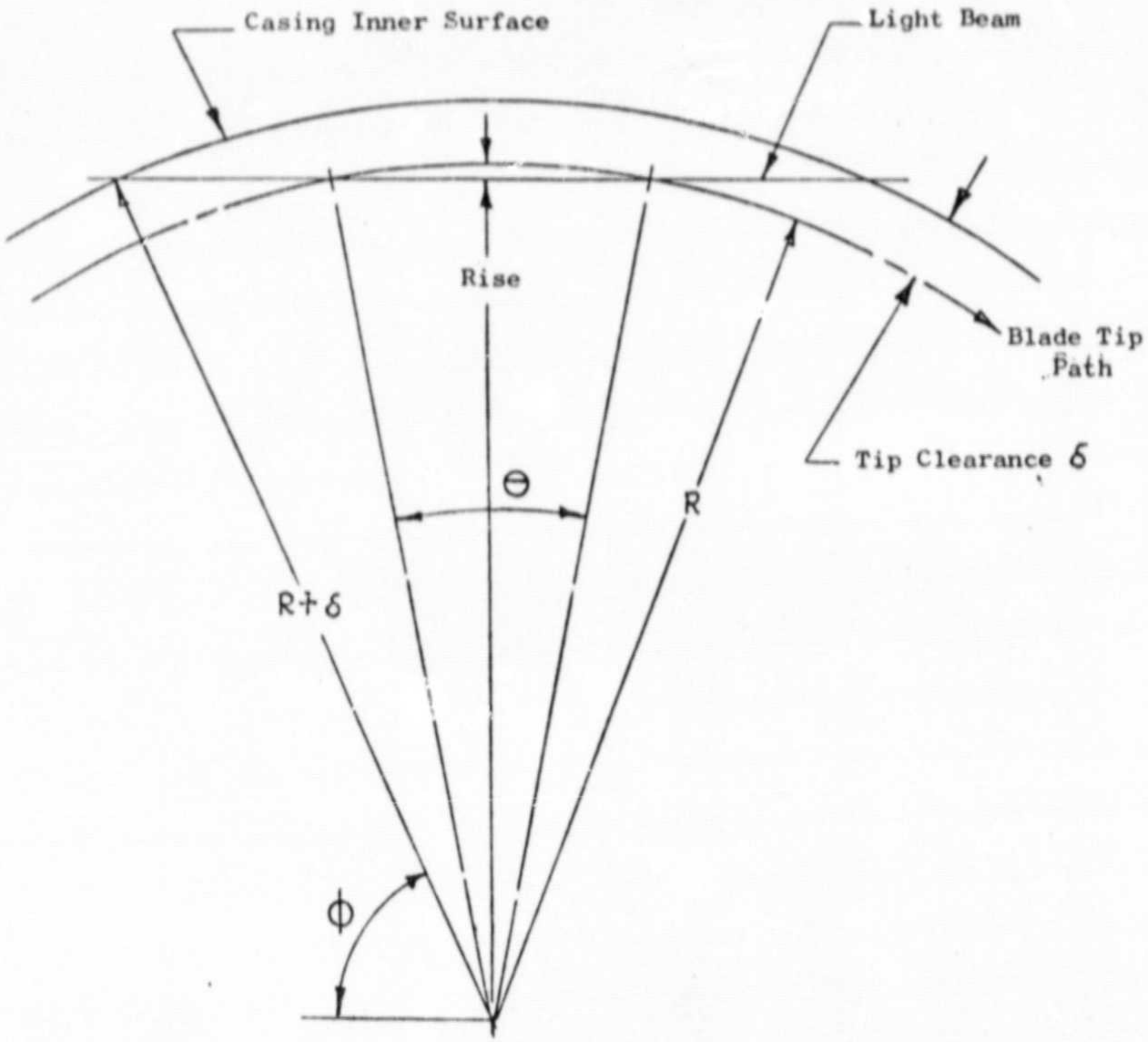


Figure 1 Sensing Concept Of Optical Tip Clearance Sensor



$$\delta = \frac{R\cos(\alpha t_1/2t_2)}{\sin\phi} - R$$

Figure 2 Optical Tip Clearance Sensor Concept Geometric Relationships

SENSOR APPLICATION

The Turbine Area

The optical tip clearance sensor was originally conceived for application to the engine turbine area. In this case, typical sensor measurement ranges were on the order of 0.35 mm (0.014 inches). Upon closer investigation, it was seen that the turbine environment and structure complexity are such that would require substantial development in order to solve several problems particular to the turbine. The extreme temperatures reached in the tip clearance sensor mounting region dictate special design emphasis on thermal effects. Due to the complexity of the turbine shroud assembly and surrounding structure, space for mounting the tip clearance sensor is at a premium. In addition, circumferential temperature variations and shroud segment forces tend to cause distortion of shroud assembly roundness and concentricity. Given a particular engine for turbine tip clearance sensor application, the above aspects would require in-depth study.

The Compressor Area

Under NASA-Lewis direction, the optical tip clearance sensor designed for this Contract was to have its application in the compressor region of the TF34 engine. This particular compressor consists of fourteen (14) rotor stages with a casing material of 6 Al-4V titanium or AMS 4911. It was decided to plan for mounting the sensor to measure stage nine (9) rotor tip clearance. Air flow at this stage runs up to about 377°C (700°F) and experiences pressures up to 1.3×10^6 N/m^2 (190 psia). Take off speed is 17200 RPM. Figure 3 shows an overall view of the TF34 compressor region of interest.

LAB EXPERIMENTS

Purpose

Concern over the design of the optical circuit of the tip clearance sensor produced the need for laboratory modelling of the proposed concepts. Experiments were therefore formulated to determine the following:

(1) The problems associated with producing a very narrow beam of light over the active region of the optical circuit.

(2) A feel for the components needed for optical circuit efficiency resulting in an acceptable detector signal/noise ratio and response.

(3) The effects of diffraction of the light beam on the detected signal, as a blade begins to interrupt the light beam (static tests).

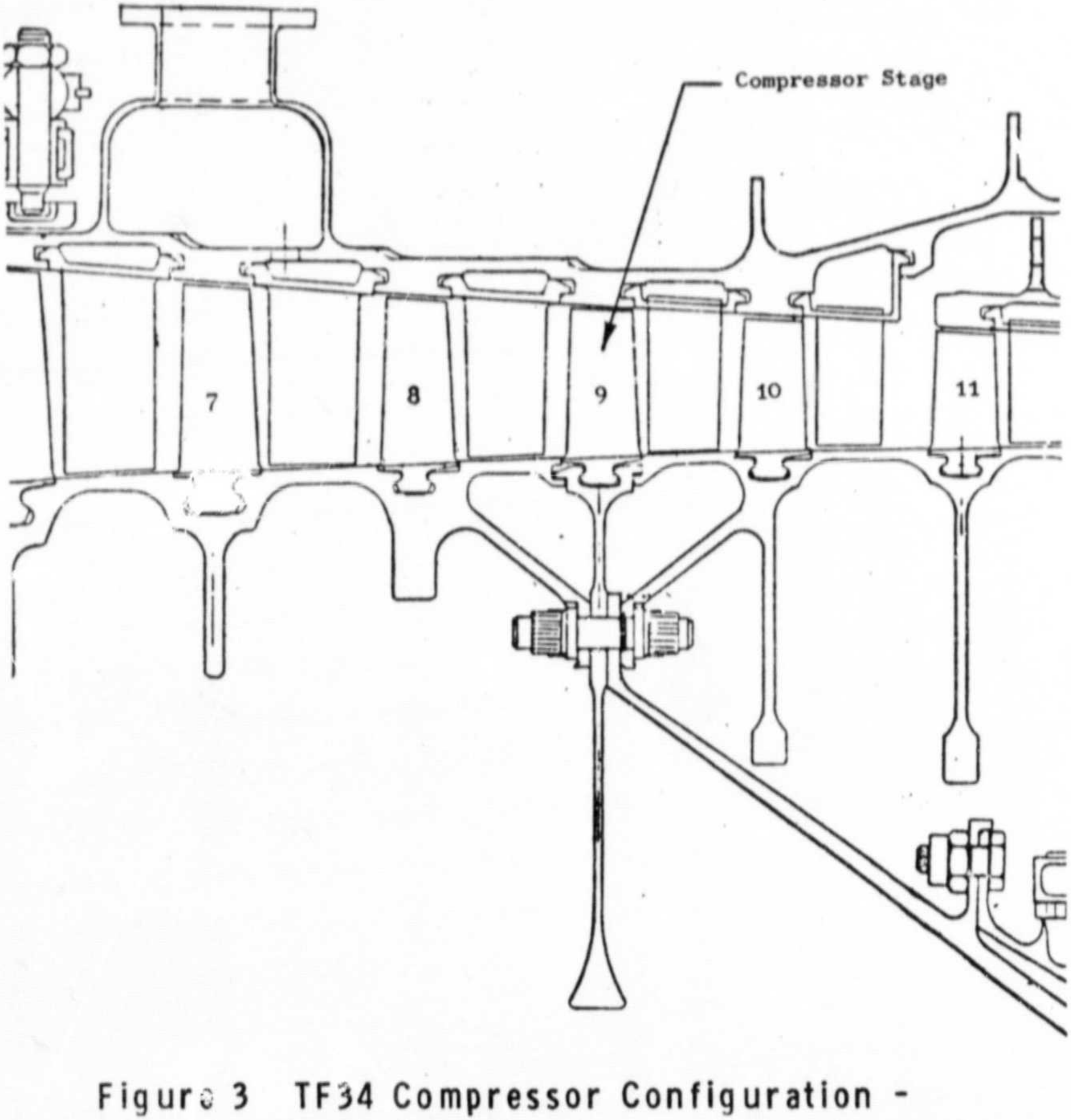


Figure 3 TF34 Compressor Configuration - Application Of Optical Tip Clearance Sensor Design

Set Up

The basic optical components of the sensor were positioned in an optical bench set up (see schematic, Figure 4). The components chosen were a first cut attempt at demonstrating the sensor concept feasibility. The light source was a standard 18.2 watt microscope intensity lamp, focused into the input fiber optic cable, which consisted of a bundle of fourteen (14), 0.099 mm (0.0039 inch) core diameter glass fibers. The output tip of this cable was configured into a single row of fibers. The input lens was an optical crown glass plano-convex with an anti-reflection coating; no output lens was used. A state-of-the-art PIN Silicon Photodiode/operational amplifier combination served as the photodetector. The components were spaced to produce a theoretical 0.0254 mm (.001 inch) thick geometrical image at the center of the clearance sensing region. The photodiode/op amp output voltage was displayed from both a digital voltmeter and an oscilloscope. Different sized aperatures were used to very the light beam thickness.

Results

The experiments helped to demonstrate the limitations and tradeoffs involved in producing a narrow light beam. The data showed that as the aperture size was decreased in an effort to decrease the overall light beam width, the effects of diffraction limited the extent of narrowing that could be achieved. It was concluded that the light beam thickness cannot be made small enough to render it negligible in the clearance calculation, although signal triggering at the half intensity light level, as the blades pass through the beam, should still result in an accurate clearance measurement.

An adequate light source/detector combination was not demonstrated in the experiments although a first cut feel was gained for what optical components are required. It was estimated that the optical energy reaching the photodiode should be increased by a factor of 10^4. This gain can partially be achieved by optimizing the optical component sizes and spacings, but major emphasis should be placed on techniques to pump more optical energy into the input cable using a more intense and directional light source.

Diffraction will cause distortion of the light beam as a rotor blade passes. Calculations of these effects are very complex. Further experimental investigations of the light intensity variations produced by different beam/blade positions must be done.

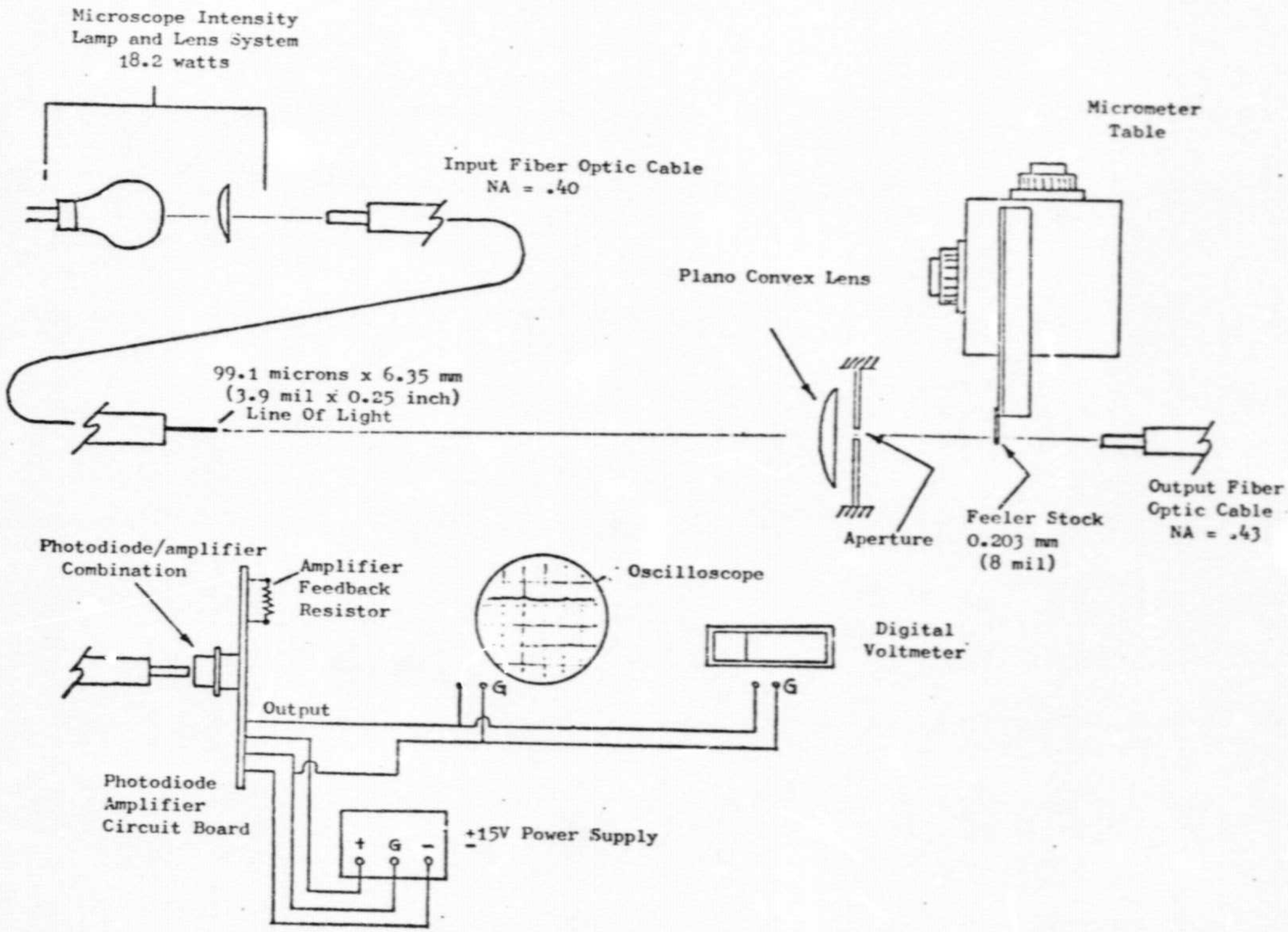


Figure 4 Tip Clearance Sensor Optical Circuit Lab Experiment Schematic

PRELIMINARY DESIGN

Division of the optical tip clearance sensor into its four basic subsystems is shown schematically in Figure 5.

Optical Sensing Elements

The optical sensing elements subsystems is defined for the tip clearance sensor as those components between the input and output fiber optic cables. These elements must modify the incoming fiber optic light into the form of a very thin beam as it passes through the compressor region, and transmit the resulting light pulses to the receiver cable. The input lens focuses an image of the input source at the center of the active sensing region. The aperture reduces the beam size. The output lens focuses the transmitted beam into the receiver cable.

Figure 6 shows the optical sensing elements as they mount in a conceivable rig-mounted sensor frame. Techniques for incorporating optical material components into a metallic sensor framework have been established through General Electric's in-house experience. In addition, procedures have been developed for successful mounting to the TF34 compressor casing using standoff pads.

Source/Detector Subsystem

The light source produces the sensor's optical power. Enough power must be generated such that the photodetector can respond with an adequate signal to noise ratio and speed of response. As mounted in the electronic control environment, the operating temperature range is -54°C to 121°C (-65°F to 250°F). Other considerations are power dissipation and physical size. Although a definite choice has not been made, possible alternatives are incandescent reflectors, focused tungsten arc lamps, zenon point sources, and small lasers.

The detector serves as the interface between the optical clearance signal and the digital electronics. It should have a small active area to minimize junction capacity and thus secure an output rise time of less than one microsecond. It too will be mounted in the electronics environment. The simplest solution could be a silicon photodiode with separate or integral amplification. However, Avalanche detectors, although more expensive and requiring a separate power supply, are superior.

Fiber Optic Cables and Connectors

The input fiber optic cable transmits light from the light source to the optical sensing elements region. Optical coupling at both ends of this cable is the most important factor in the sensor's optical efficiency. At the source end, the cable numerical aperture (NA) should be no larger than necessary to gather in as much of the available light as possible. A circular bundle configuration provides symmetry and reliability. At the sensor end, the fibers will be configured into a single parallel row, acting as the object tip for the projected thin light ray. A minimum NA will minimize spread of the beam towards the input lens and aperture.

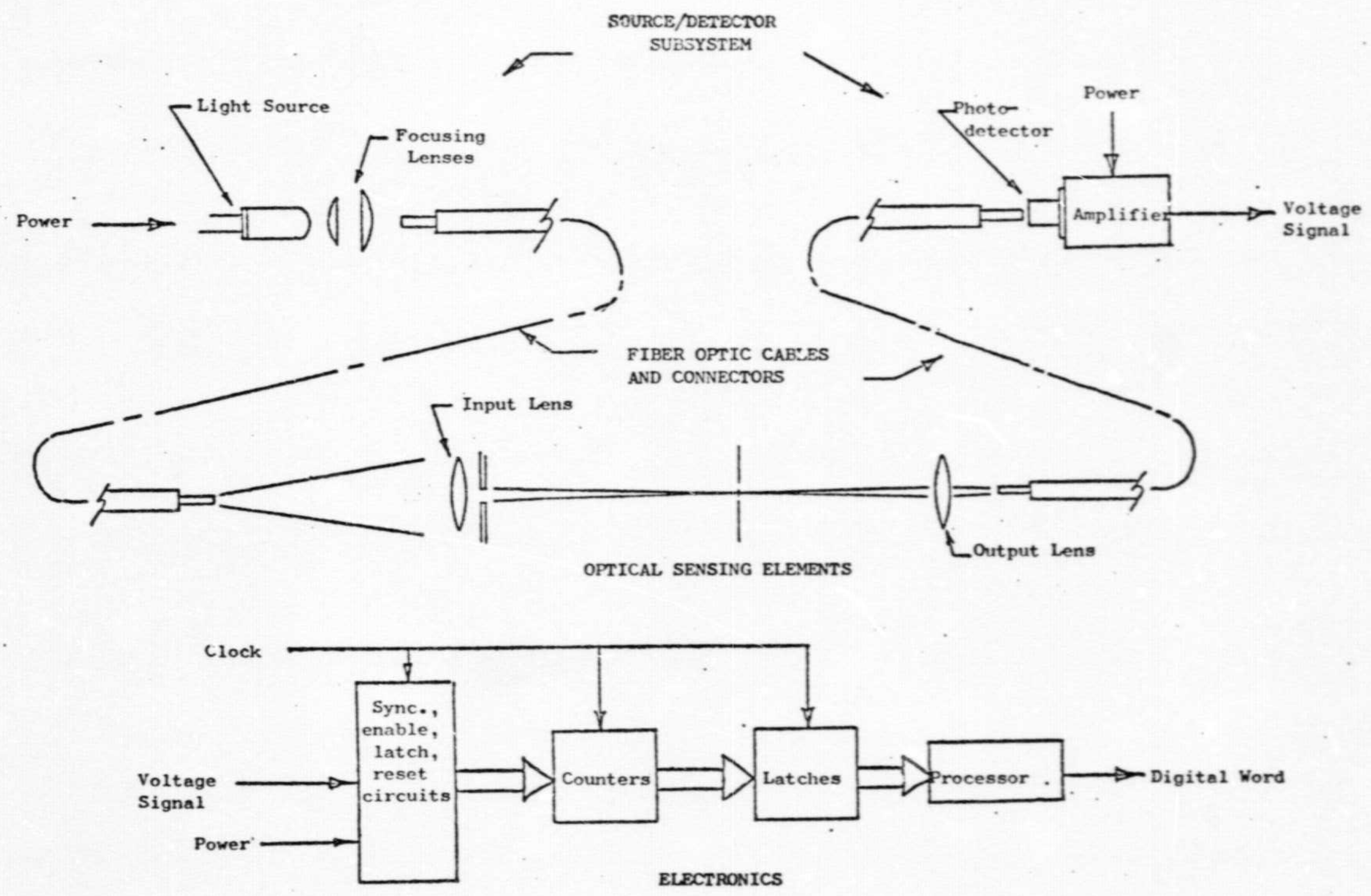


Figure 5 Four Basic Subsystems Of The Optical Tip Clearance Sensor

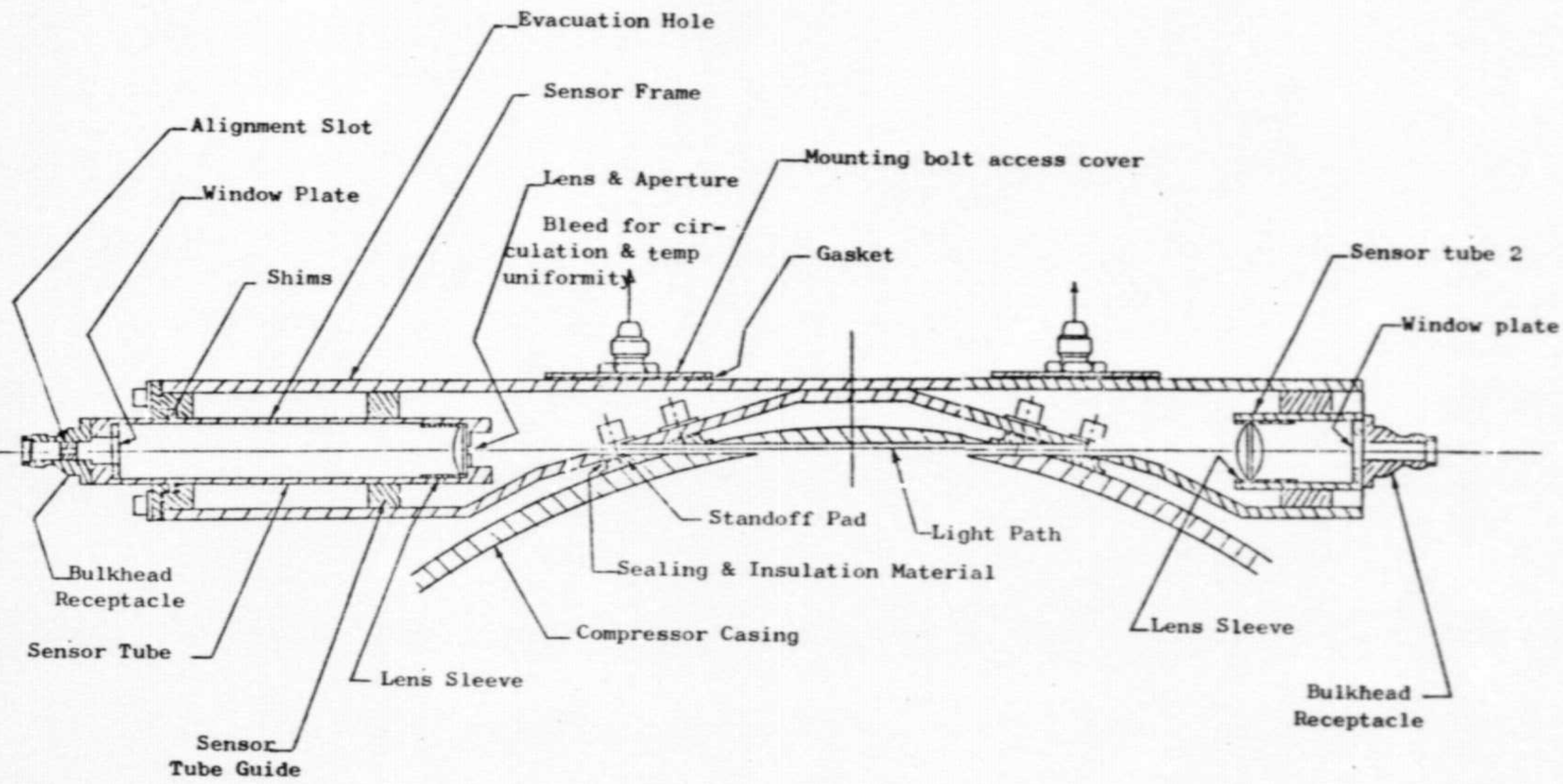


Figure 6 Conceivable Rig Mounted Frame For Tip Clearance Sensor Optical Sensing Elements

The output fiber optic cable must capture the intermittent light signal from the sensing area, transmitting it to the photodetector. Its active diameter is determined by the projected ray image size and the detector's active area.

Mechanical coupling of the cables will be accommodated by using stainless steel cable plug/receptacle type fittings as shown in Figure 7. These provide for close coupling at both the source and detector junctions, as well as quick and accurate assembly at all end positions.

Electronics

Sensor electronics are required to transform the alternating voltage signal from the photodetector into a digital clearance word. The overall electronics block diagram is shown in Figure 8. Other inputs include power supplied for the operational amplifiers, digital chips, microprocessor, and memory units. Output clearance information could include average clearance and minimum clearance over a cycle of rotor blade measurements, as well as a continuous clearance signal. Clearance is determined by digitally counting the time of light blockage t_1 and the time of blade passing t_2, and substituting into an equation of the form,

$$\delta = A \times \cos(B \times t_1/t_2)) - C$$

where A and B are physical constants and C is a systematic error correction factor. Internal hybrid substrates and discreet electrical components would be packaged comparable to existing electronic controls.

SENSOR QUANTITATIVE PREDICTIONS

Measurement Range

Sensor clearance measurement range depends upon the radius of the rotor and the number of rotating blades. For the TF34 stage 9 compressor, with 88 blades and a 17.46 cm (6.875 inches) rotor radius, the range is 111 microns (.00438 inches) for one sensor. An increased range can be obtained with multiple sensors.

Accuracy

Maximum sensor resolution occurs at the zero clearance, maximum speed condition. Using a 7 MHZ digital clock and at, say, the TF34 takeoff speed of 17200 RPM, maximum resolution is 0.813 microns (.032 mils).

A clearance measurement error occurs due to compressor rotor blade thickness. The time of light blockage is made too long due to the leading and trailing edges of the blade blocking and unblocking the light beam. For a blade circumferential thickness of 0.686 mm (27 mils), this error can be as high as 12.7 microns (0.5 mils). This error is systematic and can be compensated out by the electronic software.

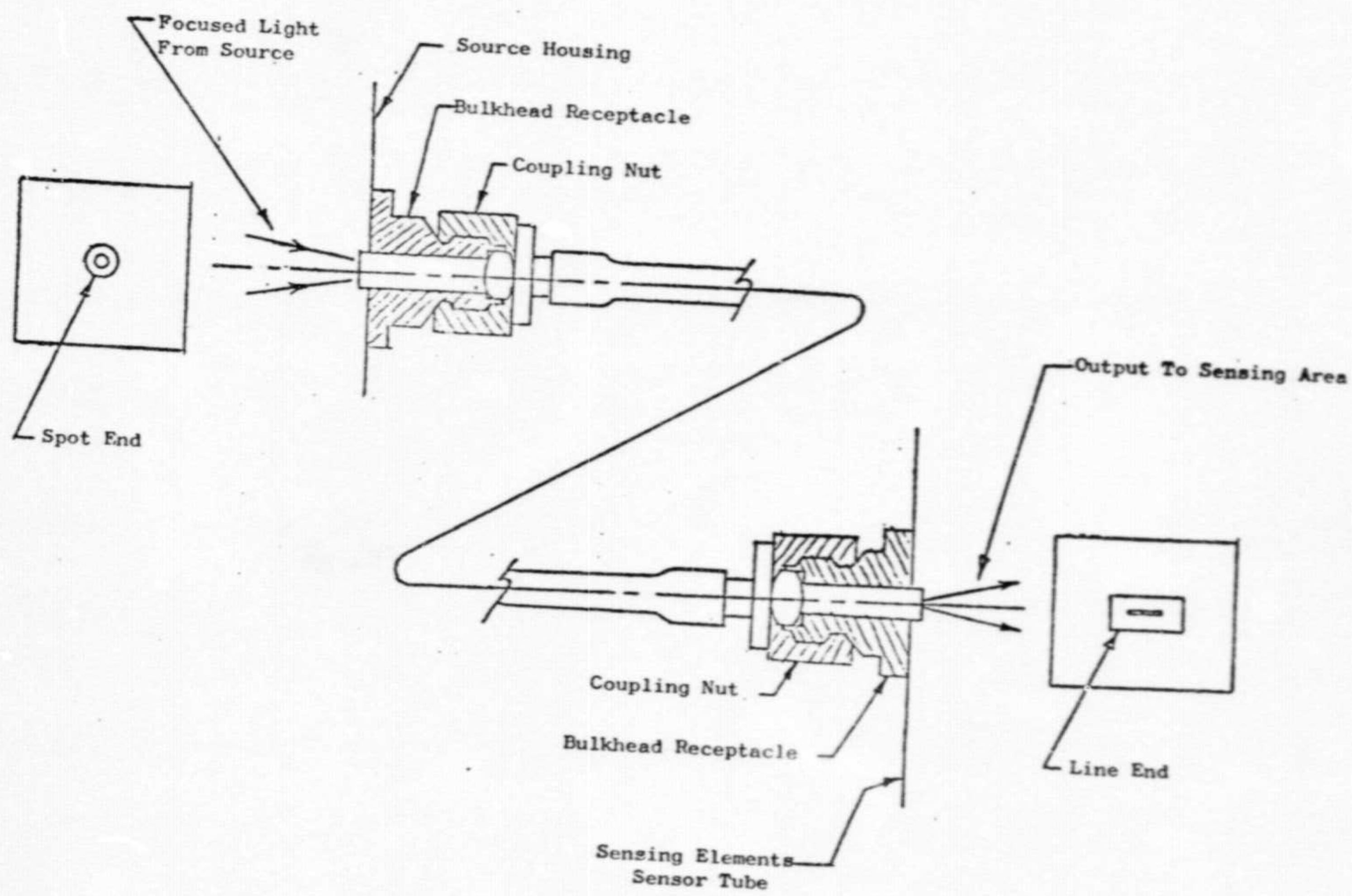


Figure 7 Typical Input Fiber Optic Cable Plug/ Receptacle Configuration

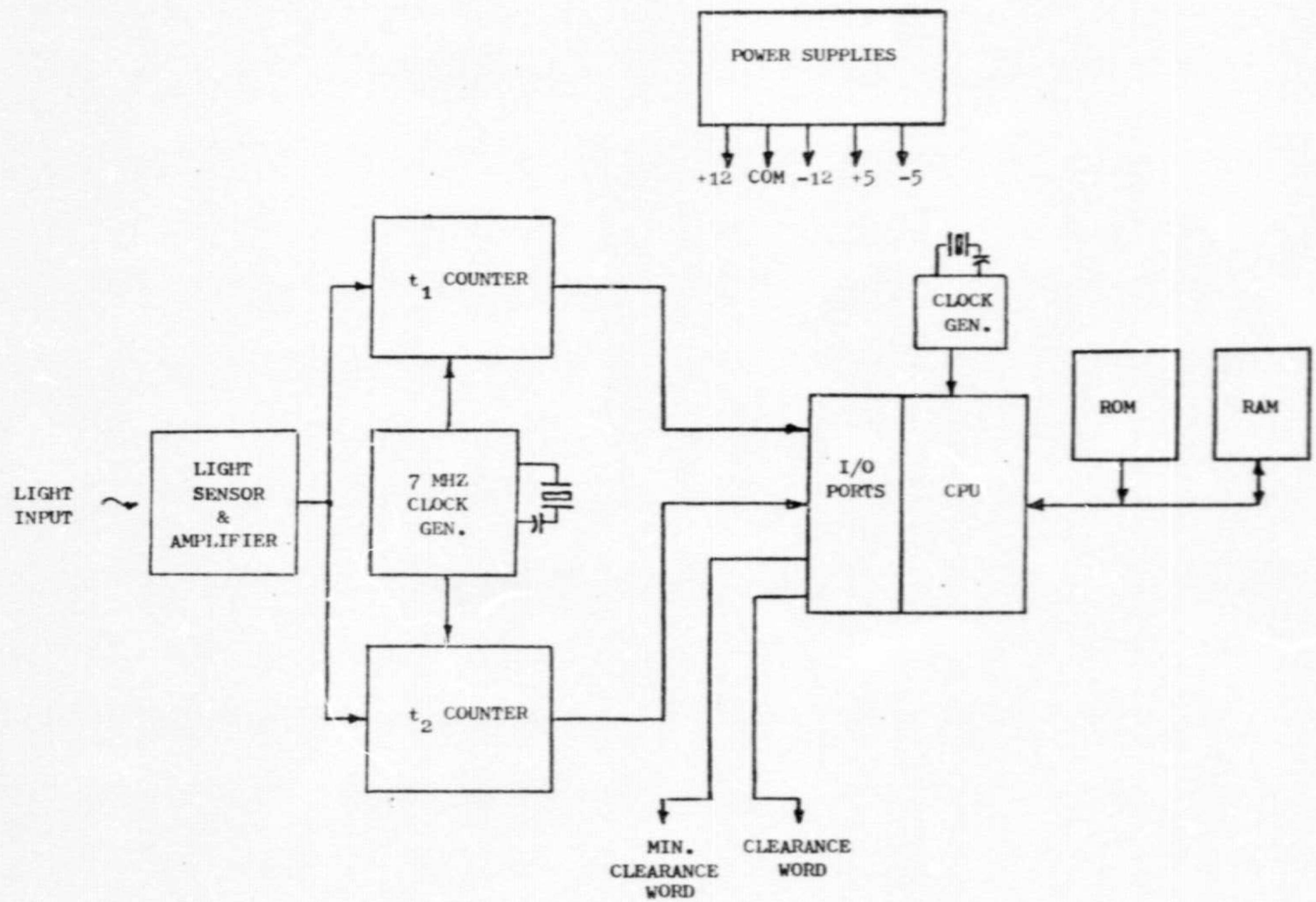


Figure 8 Optical Tip Clearance Sensor Signal Processing Electronics Block Diagram

Various types of blades as well as dimensional tolerances contribute to blade spacing variations within any particular rotor. This affects the sensor light pulse signal lengths and the clearance measurement accuracy. Based on standard blade spacing variations, the affect on clearance measurement is negligible. However, excessively wide or narrow blade spacings cause erroneous clearance signals which must be disregarded by the electronics software or used as one/rev markers.

A wider light beam through the sensor active area results in a less abrupt attenuation of the light signal as a compressor blade passes, and a less accurate tip clearance calculation. As analyzed in the laboratory experiments, signal triggering at the half intensity position is necessary to minimize this effect.

Transient Response

A short time is needed by the electronic processor to do the clearance calculation after the time intervals t_1 and t_2 are measured. For an 88 blade compressor stage it is suggested that every third blade be measured, requiring three revolutions to complete a cycle. At takeoff speed of 17,200 rpm, this corresponds to a clearance measurement output every 118 microseconds.

Sensitivity To Environment

Temperature capabilities of the sensor components have been briefly investigated. It appears that the light source, photodetector, and fiber optic cables are all sensitive to the engine mounted environment.

Power Requirements

The sensor electronics, including the photodiode but not the light source, will consume approximately 18 watts. For comparison, the Full Authority Digital Electronics Control (FADEC), being developed in the Contractor's advanced controls program, dissipates on the order of 200 watts.

RECOMMENDED DEVELOPMENT AREAS

Light Source and Detector Choices

Before any subsequent feasibility demonstrations, it is imperative that the sensor light source and detector choices be made. Especially in the case of the light source, several possibilities should be identified. A static laboratory experiment should again be performed to verify that adequate optical power has been attained over the temperature range.

Sensor Frame Design

Mechanical design of the sensing elements' frame involves matching with the compressor casing such that the frame retains its straightness and integrity during casing thermal radial growth cycles, distortions, and vibration. Vibrational modes of the sensor itself should also be studied.

Thermal Effects

The sensing elements subsystem requires a thermal effects analysis to assure continued accurate performance over the temperature ranges. For example, thermal growth will affect such items as the image focal point position in the gas flow region and the aperture diameter.

Sensor Range Increase

The future applications of this optical tip clearance sensor will probably demand a substantial increase in its measurement range. As a feedback sensor in an active control system, the sensor would need to provide an error signal in a range on either side of some null position. Used as a clearance monitor or mapping device would require the sensor to measure many times its single beam capability.

Turbine Area Application

Optimizing engine efficiency through clearance control requires primary application to the turbine area. Due to the major energy extraction by the turbine, modest increases in weight and cost are offset by the performance gains and resulting decreases in fuel consumption that are achieved.

PLAN FOR FEASIBILITY DEMONSTRATION OF OPTICAL TIP CLEARANCE SENSOR

OBJECTIVES

The overall objective is to establish a detail test plan for the optical tip clearance sensor such that when satisfactorily completed, the tests show that the sensor concept is feasible and warrants continuing development for applications to digital electronic propulsion control systems on commercial and military aircraft. The sensor designed and built for the test is to be a laboratory model, designed primarily to show that this concept can be used to measure a spin rig rotor casing clearance at an accuracy of $\pm$ 12.7 microns ($\pm$ 0.5 mils). Demonstration of mechanical and thermal integrity would be done by analysis to show a high degree of confidence towards engine application.

The rotor to casing clearance changes will be provided by the spin rig rotor elastic radial stress growth due to centrifugal forces, as the rig speed is increased. With this as the input to the mounted sensor, recorded measurements will be made of the input versus sensor output during steady state calibration and rotor accels. A touch probe will provide a comparison clearance measurement.

TEST PLANS

Set Up

The demonstration will include all four subsystems of the optical tip clearance sensor. Bench checkouts of the subsystems will be performed prior to testing as a unit on the rig. The spin rig will consist of a facsimile of the TF34 compressor, rotated to simulate, as far as practical, compressor blade passing frequencies. A touch probe will be mounted to measure minimum tip clearance at the same location as where the optical sensor measurements are taken. Figure 9 shows the spin rig casing set up. Provisions will also be made to record sensor vibrational g level, for engine comparisons, and to observe the photodiode output waveform, in order to check where signal counting is initiated and terminated.

Demonstrations

Because of its small measurement range, the optical sensor will be able to actively measure clearance over only a particular band of the spin rig rotor's radial excursion over the speed range. After the touch probe clearance versus speed calibration, the optical sensor will be shimmed into position and calibrated over one or several of these speed bands. Accels and decels through these ranges will demonstrate sensor response and any hysteresis. An incremental speed change will reveal sensor resolution capabilities.

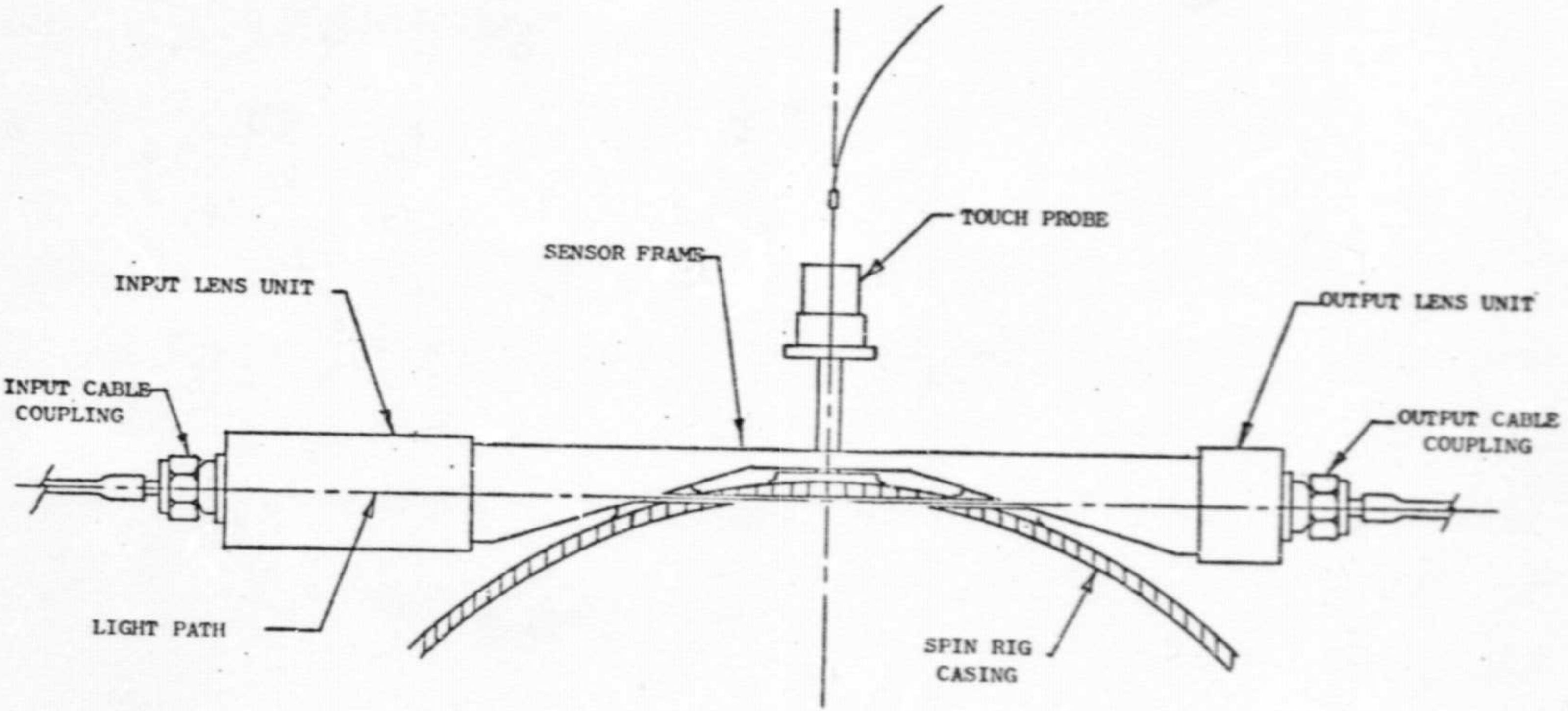


Figure 9 Spin Rig Casing Set Up For Optical Tip Clearance Sensor Feasibility Demonstration

DISCUSSION OF OPTICAL SENSOR PROGRAM RESULTS

Task 1 resulted in the choice of the optical digital tip clearance sensor, from among those sensor concepts generated, as the concept reflecting the highest confidence in feasibility and in future application payoff. This concept was pursued throughout the remainder of the program.

Quantitative performance predictions, produced in Task 2, firmed up the soundness of the sensor concept. Sketches, drawings, fabrication methods, functional descriptions, and environmental requirements were provided for the satisfactory operation of the sensor subsystems. All components were assessed as to their potential for providing reliable operation in an engine-mounted environment. Several areas requiring development, before the concept becomes viable in a practical sense, were suggested.

A feasibility test plan was produced in Task 3. Through this demonstration, involving a careful choice of optical components, a decision can be made as to whether the optical sensor concept warrants continued effort towards engine application.

CONCLUDING REMARKS

This Final Report summarized the work performed under a program for the Analysis and Preliminary Design of Optical Digital Sensors For Propulsion Control. An optical, digital tip clearance sensor was the item analyzed. Performed laboratory experiments exposed no conceptual roadblocks to a continued development effort. Performance predictions show that application of the sensor in an active closed loop clearance control system is yet a feasible goal. Satisfactory operation of the optical circuit over the temperature range should next be demonstrated, followed by detailed design for testing on a spin rig.