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TECHNOLOGY PROGRAM

INTEGRATED CONTROLS AND HEALTH MONITORING FIBEROPTIC SHAFT MONITOR FINAL REPORT TASK E.5

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INTEGRATED CONTROL HEALTH MONITORING
FIBEROPTIC SHAFT MONITORING FINAL REPORT

FOREWORD

This document represents the final report to the National Aeronautics and Space Administration for work performed under Task Order E.5 to Contract NAS 3-23773. This task addressed an Integrated Controls and Health Monitoring (ICHM) technology requirement for the Orbit Transfer Rocket Engine Technology Program. This is a summary report with all material discussed herein presented to NASA program personnel at oral presentations or in the contractually required monthly program reports during active work on the task.

At Rocketdyne, the principle investigators were Messrs. P. Coleman, H. Darejeh, and J. Collins. Mr. R. P. Pauckert was the Program Manager, and Mr. T. J. Harmon was the Project Engineer. The NASA LeRC Task Monitor was Marc G. Millis.

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Summary

Shaft dynamic behavior is a critical parameter in evaluating rocket engine turbopump component condition. Wear, erosion, spalling, pitting, and other surface degradation processes result in measurable changes to shaft dynamic motion. The measurement and interpretation of characteristic shaft motions can provide vital data for determining which components may be degrading, and to what extent the degradation has progressed.

This report describes the development of a turbopump shaft monitoring system using fiberoptic sensors. The system is intended to monitor shaft axial displacement, shaft orbit and shaft speed at up to 200,000 rpm. To provide these optical measurements, a method was developed to use a surface pattern on the shaft to modulate light as a function of shaft axial and radial motion, and speed. A fiberoptic deflectometer was adapted for use as the optical sensor. A suitable pattern was found to be eight triangles of non-reflective material whose change of reflectivity from that of shiny titanium shaft modulates the light intensity received by the deflectometer. This modulation in light intensity and the associated time periods of the change in intensity indicate shaft axial and radial position and shaft speed. Extraction of these measurements is accomplished by a signal processing unit. The signal processor was designed to take the output of two orthogonal fiberoptic deflectometers which view this pattern, and to provide real-time voltages related to the amplitude of x,y and z motions, as well as speed.

The project required:

- adaptation of the deflectometers to be used as the optical pickup

- development of a technique for economically applying a precision pattern on the shaft

- selection of an appropriate shaft surface treatment for placement of the pattern

- development of an electronic signal analyzer to process the modulated deflectometer signal for extraction of the shaft motion and speed information

Performance Tests Summary:

1. An evaluation was done of metallized fiberoptic probe tips sealed with solder, and of standard deflectometer probe tips made by Mechanical Technology Inc. (MTI). The standard MTI production probe tips were manufactured with epoxies: Crest 810A&B, M-Bond 43B, and Hexcel 3124. The metallized tips and the Crest 810A&B tips were pressure-tested at Rocketdyne to determine leakage at the interface between the fiber

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bundle and the stainless steel ferrule. Hexcel 3124 was also pressure tested at a separate pressure joint in conjunction with other tests.

2. Laboratory tests of the shaft position monitor were carried out using two standard laboratory 1/8" fiberoptic probes (by MTI) viewing a 2-inch diameter Titanium disk spinning on a fabricated benchtop tester at up to 10,000 rpm.

Results

1. Hexcel 3124 was selected as the adhesive sealant of choice for bonding the deflectometer probe fibers for use in the LH_2 environment. Special heavy-duty, thick-walled probe tips were added to provide probe rigidity while a small fiber bundle diameter was selected to lower the susceptibility of the fiber to slippage when the face is exposed to high pressure.

2. An electronics analyzer was designed and built to work with the optical signal to provide the following shaft motion sensitivity:

   Axial motion: 140 millivolts/mil ± 0.34 mils over a range of 30 mils
   Radial motion: 8.72 millivolts/mil ±0.05 mils over a range of 50 mils.

Conclusion

The fiberoptic shaft monitor has been developed to provide real-time measurement of vital turbopump shaft dynamic parameters. Precise knowledge of the turboshaft's dynamic motion will be of high value in the interpretation and correlation of measurement data from other sensors for the determination of the condition of critical turbopump components.

Introduction

Accurate measurement of shaft speed, and shaft axial and radial motion is essential in turbopump performance studies. Also, knowledge of shaft motion history during normal operation may provide crucial information in the determination of probability of wear and possible reusability and fitness of bearings and seal surfaces in the rotating turbopump stack. In high speed rocket engine turbopumps that perform up to 200,000 rpm, however, the measurement response rates and shaft motion tolerances are outside the abilities of traditional commercial shaft monitoring devices. Thus, the development of a precision optical shaft monitoring system may be a crucial element in the development of a viable engine condition monitoring system.

This program is aimed at developing an optical shaft monitor to provide high precision motion measurement (on the order of tens of micro-inch sensitivity) over a wide dynamic range. Also, this system will provide both axial and radial motion, as well as speed from the analysis of the output of two optical sensors placed perpendicular to the shaft. This system eliminates the need for

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two of the four ports that would normally be required in the turbopump to make these shaft motion measurements: two ports for radial motion, one port for speed, and one port on the shaft end to monitor axial motion. Furthermore, this system provides a way of measuring shaft axial motion without interfering with the geometry of the pump outlet area (typically wrapped around the pump end of a combined power/pump shaft) or with the turbine inlet area (at the other end of the shaft).

Background

In previous work prior to this contract, the feasibility of measuring shaft motion (x,y,z) and speed by monitoring special patterns on the shaft was experimentally validated in the lab. Also, a photo-reduction technique for making a high resolution stencil for the pattern on the shaft was evolved and tested. Finally, a titanium surface treatment called Tiodizing was selected and tested. This program builds upon this previous work and takes on the tasks of adapting the optical sensors to the cryogenic conditions of the hydrostatic bearing tester as well as developing a demonstration electronic signal processor to decode the shaft data.

Although this analyzer was built to process signals from a pair of fiberoptic sensors, laboratory experiments have shown that other sensor approaches in combination with a shaped plated strip on the shaft can also be made to work quite well. For example, with proper shaft surface deposits and machining, either a ferromagnetic torquemeter or an inductive or capacitive proximeter can be adapted to work with this processing technique, although with reduced speed, sensitivity and range. The shaft dynamic motion analyzer is intended to be part of a comprehensive condition monitoring system for reusable rocket engine turbopumps.

In addition to higher precision, reliability, and improved sensitivity and dynamic range of an optical shaft monitor, this measurement system requires fewer sensor ports than conventional sensor approaches for obtaining these same shaft motion measurements. Also, conventional inductive and capacitive proximetry sensors usually require special machined notches on the shaft to provide measurement, distance calibration and revolution counting. Such notches on a high speed shaft might cause performance degrading turbulence in liquid hydrogen. Thus the optical sensor approach, that did not require changes to the shaft circumferential geometry, was selected. The resulting shaft position analyzer system that was developed in this program is shown in Figure 1.

Technical Description

The sensors are configured to detect changes in reflected optical energy from a triangular pattern on a one-inch diameter shaft (see Figure 2). One sensor is positioned normal to the shaft in a horizontal (x) position; the second sensor is positioned normal to the shaft in the vertical (y) position. The absolute

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Figure 1. Shaft Position Analyzer System Performance Testing

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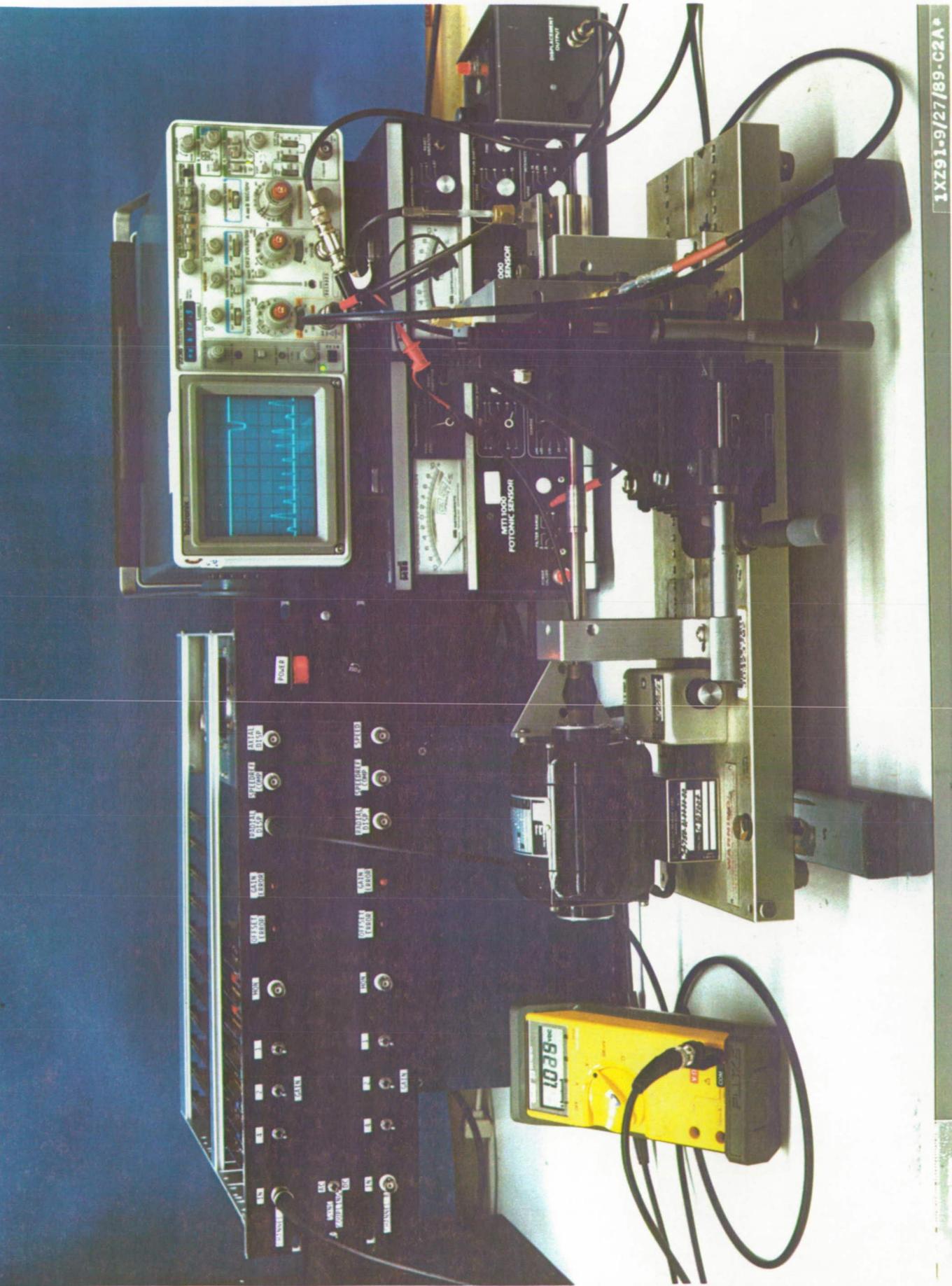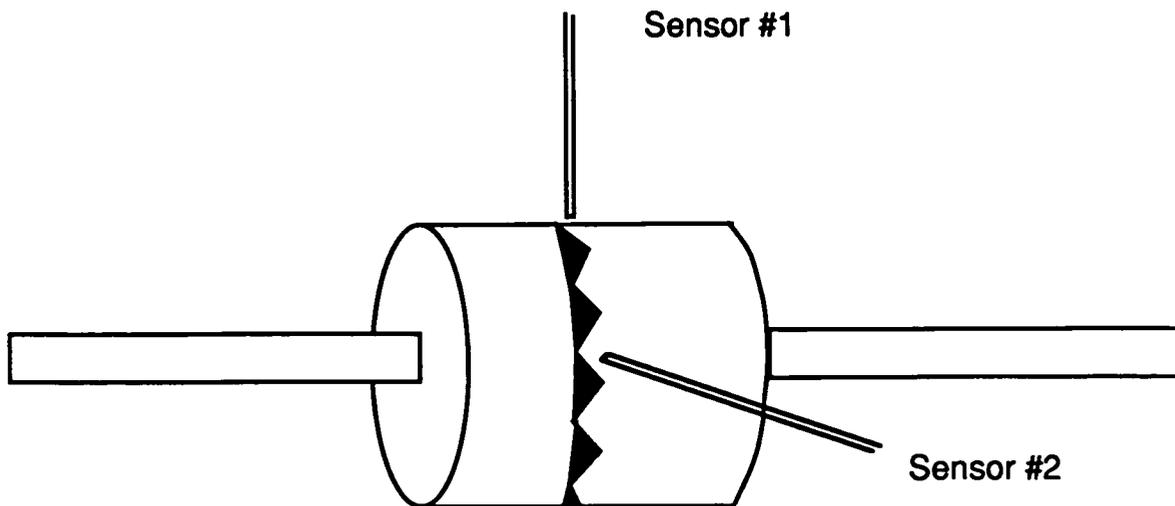
Figure 2   Target disk surface pattern

axial (z) position of the sensor relative to the center of the triangular pattern on the shaft is indicated by the ratio of the periods of light and dark patterns detected on the shaft. Shaft velocity is detected as the rate of detected triangular patterns. Radial position on a relative scale may be determined from measurement of the magnitude of changes in reflected light intensity created by the triangular pattern in each axis (see Figures 3 & 4).
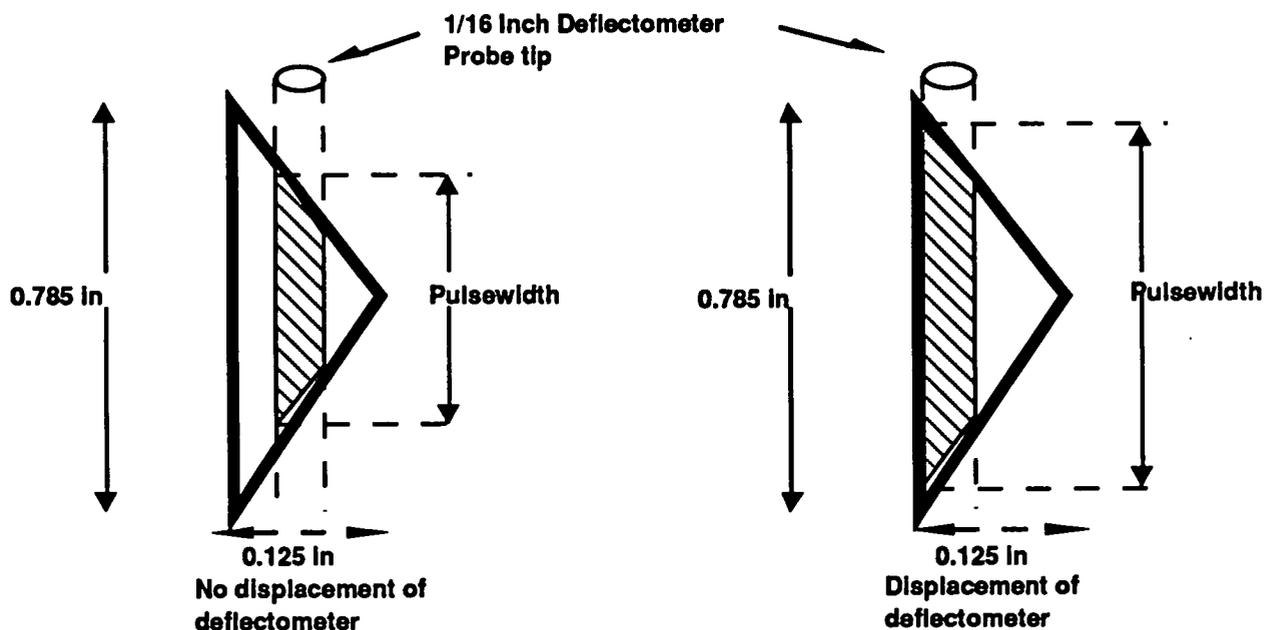
Figure 3   Probe view of pattern
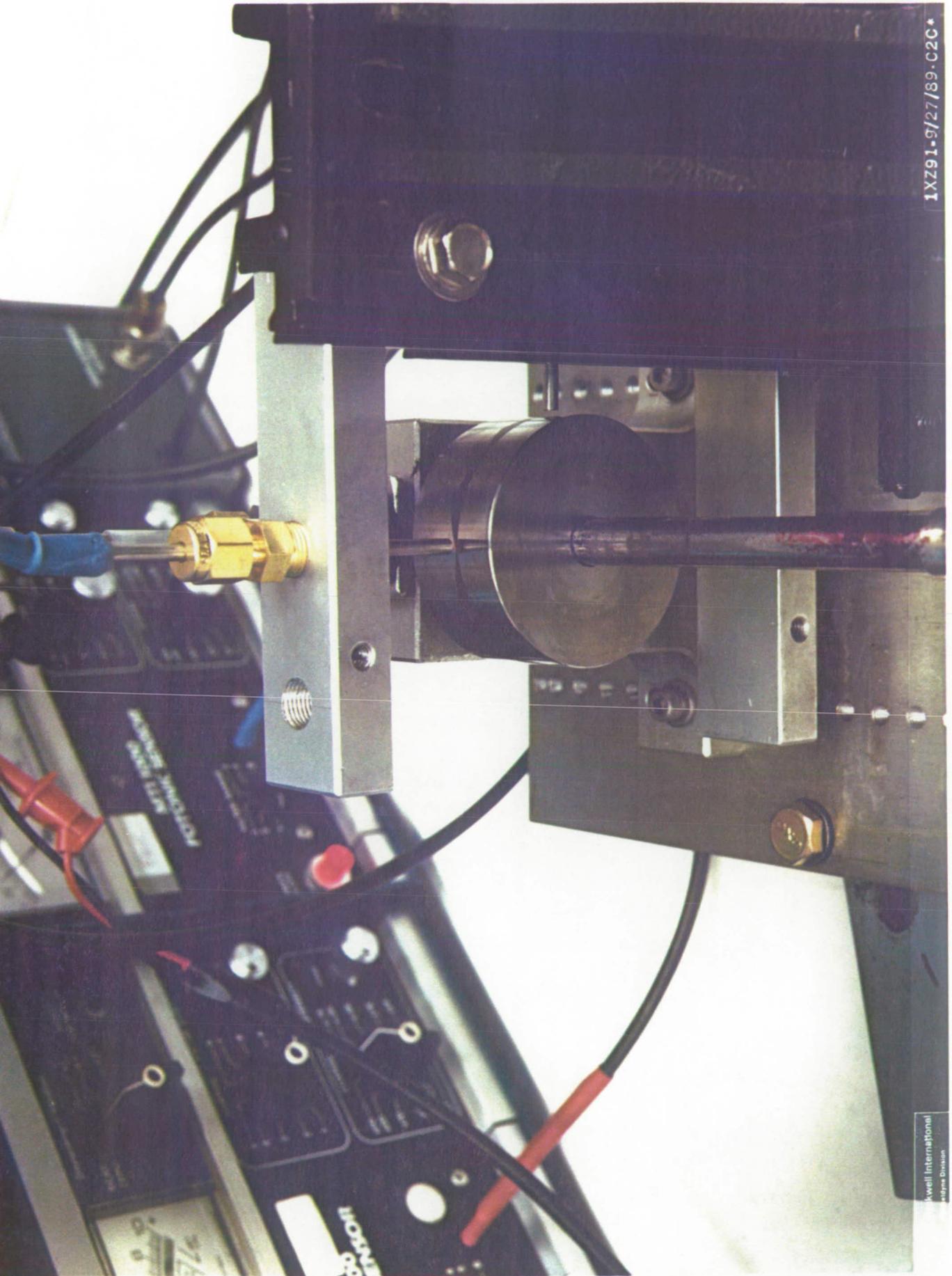
Figure 4. Close-up View of Target Disk and Surface Pattern

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The triangular pattern on the shaft has eight identical symmetric triangles placed end to end along the circumferential surface of the shaft. The height of the triangles in the direction parallel to the axis of the shaft is nominally 0.125 inch. The initial focal point of each optical sensor is positioned to the nominal axial midpoint of the triangular pattern. The measured axial position from the signal conditioning unit indicates the absolute deviation of the focal point of the sensor from the exact midpoint of the triangular pattern on the shaft. The range of axial measurement is nominally about 30 mils. The measured resolution (minimum resolvable motion increment) is nominally 0.030 mils at shaft speeds up to 10,000 rpm. Since the measurement is based on the ratio between the light and dark patterns, the resolution is expected to be relatively unchanged up to the frequency response limit of the deflectometers (about 140,000 rpm).

Each sensor output is DC coupled to the input amplifier in the signal conditioning unit (see Figure 5). The gain and input offset are set by the operator for maximum sensitivity with no indication of gain or offset errors. When properly adjusted, the amplifier output will fluctuate approximately symmetrically about 2.5 volts. When the amplifier is set as described above, a DC reference is automatically set in the signal conditioning unit, relative to the intensity of reflected light when the sensor encounters the dark portion of the triangular pattern. Radial position, on a relative scale, is determined by measurement of the average intensity of reflected light (relative to the DC reference) when the sensor encounters the light portion of the rectangular pattern. Radial position measurements are updated 16 times per shaft revolution.

The range of the radial measurement is about 50 mils, based upon the backslope output calibration curves of the deflectometers used. The measured minimum resolution of radial motion is at least better than 25 micro-inches, at speeds up to 10,000 rpm, which is the limit of our benchtop speed and motion measurement capability.

The minimum resolution of deflectometers is generally limited by the electronic noise level of the deflectometer amplifier. However, the shaft monitor analyzer averages out a significant portion of the random instrument noise, and thus extends the useful resolution to a much lower value than is otherwise expected. Thus, we expect the actual resolution of this system to be closer to ±5 micro-inches up to the frequency response limit of the optical deflectometers (about 140,000 rpm). The analog signal from each optical sensor is converted to digital form by a flash encoder with a 0 to 5 volt range. If the signal goes negative or exceeds the range of the flash encoder, LED indicators on the front panel warn the operator of "offset" or "gain" error. One digital peak detector searches for the maximum signal level and a second digital peak detector searches for the minimum signal level. An arithmetic unit computes a value midway between the minimum and maximum levels and outputs this value in analog form as a reference for the comparitor that detects the transitions from the light and dark regions of the triangular pattern.

The comparitor output for each signal channel and the digital values from the flash encoder for each signal channel are processed with pipeline parallel

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OPTICAL SHAFT SPEED/DISPLACEMENT MONTITOR

(NEGLEDA) 1 → TO LEDS ON FRONT PANEL

(POSLEDA) 1 →

(AMPMONA) 1 → TO BNC ON FRONT PANEL

OPTICAL SENSOR A — 1 → **A/D MODULE A**

GAIN (1,2,4,8,16) — 3 →

(AD01A-08A) 8 → **AVERAGER MODULE A**

1 (COMPA) 1 →

2 (DAVGCLKA) (LAVGCLKA)

(COMPA) 1 → TO COMPARATOR MONITOR A

1 → **TIMING MODULE** → 3.125MHZ

1 (LOADL)

2 12 2

LOG PROCESSOR MODULE (ADISP) 1 → AXIAL DISPLACEMENT OUTPUT (±100mV/mil)

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DAC MODULE

(RDISPA) (RDISPB) 2 → RADIAL DISPLACEMENT OUTPUTS

1 (SLOCLK)

(SPEED) 1 → SPEED SIGNAL OUTPUT

3.125MHZ 1 → 15

(NEGLEDB) 1 → TO LEDS ON FRONT PANEL

(POSLEDB) 1 →

(AMPMONB) 1 → TO BNC ON FRONT PANEL

OPTICAL SENSOR B — 1 → **A/D MODULE B**

GAIN (1,2,4,8,16) — 3 →

(AD01B-08B) 8 → **AVERAGER MODULE B**

1 (COMPB) 1 →

2 (DAVGCLKB) (LAVGCLKB)

(COMPB) 1 → TO COMPARATOR MONITOR B

Figure 5

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arithmetic circuits to obtain the required measurements of speed, axial and radial position. Results are converted to analog form for use by the operator. The prototype model does not include a computer interface module. Future models should use a remote computer for automatic control, scaling, display and data recording.

Lab Testing

Construction of the fiberoptic probes was crucial to the successful cryogenic operation of the sensors. The major factor in the production of the sensors by MTI was the choice of sealant for the interstices between the fibers and the interface between the stainless steel ferrule and the fiber bundle. Rocketdyne ME&T personnel recommended three possible cryogenic sealant/ epoxies that might fit the requirements for operation of the fiberoptic probe: Crest 810A&B, M Bond-43B, and Hexcel 3124. Also, a metallized fiber bundle that had been sealed with solder was proposed by Spectran Fiberoptics company as a possible general purpose construction solution suitable for most of our demanding cryogenic applications (LOX as well as LH_2). Spectran provided samples to MTI for the manufacture of test probes which were provided to us at no cost for testing. Several fiber bundles with epoxy sealants were tested, as were the metallized fiber bundles.

Pressure testing of probes manufactured by Spectran and MTI was conducted in the Engineering Development Laboratory at Rocketdyne. The tests consisted of pressurizing the sensor probe tip with 1000 psi gaseous helium with the sensor and optical fibers placed in a liquid nitrogen bath (see Figure 6). For the sealant/epoxy based test probes, the Crest 810A&B and the
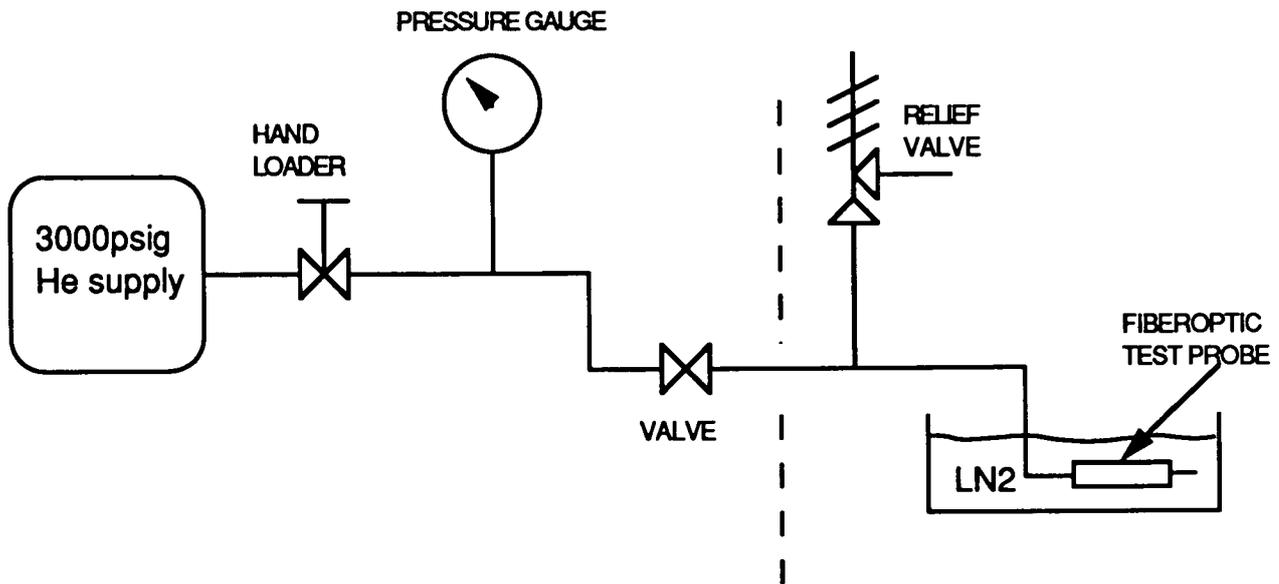
Figure 6 Cryogenic pressure testing system

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M Bond-43B were both found to be inadequate for the probe manufacture process. Crest 810A&B had insufficient bonding strength at room temperature, and the fibers shattered during the final surface finishing process. M Bond-43B was too thin to fill the interstitial pores between the fibers, and thus failed the leak test. Finally, although no sample probes were made with Hexcel 3124, we did use this bonding material to provide a joint seal in the pressure test; it was found to have good room temperature working consistency and provided adequate high pressure seal in the cryogen. The metallized Spectran probes leaked between the fiber bundle and the stainless steel ferrule when pressurized to 400 psi. On inspection it was deduced that the flux in the solder had left voids which provided a leak path. Also, the solder had not adhered to the stainless steel outer ferrule. This technique might work if a non-flux solder were used and if the outer ferrule were made of a material more compatible to solder adherence (for example Inconel). Choice of solder could be expanded, or brazing techniques could even be used if the metallized fibers were made of a material with higher temperature resistance. Since it could potentially reduce costs to instrument future cryogenic applications for the deflectometers if an off-the-shelf ruggedized deflectometer could be evolved, it would be worthwhile to pursue inexpensive metallized fiber soldering or brazing techniques in future programs.

To serve this program's schedule and budget, Hexcel 3124 was selected as an adequate choice of sealant for the deflectometer construction. Our selection of this material was based on substantial previous experience with Hexcel 3124 in and around LH_2 environments as well as observed performance adjunctive to the process of testing the other probes. A finished deflectometer probe made by MTI with Hexcel 3124 was tested with 1000 psi gaseous Helium at ambient and liquid nitrogen temperatures. No leaks were observed in the fiberoptic probe, although the teflon seal in the fixture holding the probe leaked in LN_2. These tests were repeated several times yielding the same results. After these pressure tests, the deflectometer was connected to its electronics module and functioned normally.

Because the main criteria for construction of the deflectometer probes was survivability in a pressurized LH_2 environment, and because cost containment was crucial, the probes were manufactured by MTI on a best effort basis. Thus, while the manufacturer did attain the survivability criteria, the as-delivered frequency responses of each of the four purchased deflectometers were somewhat less than the original target value (60 KHz) requested; the delivered instruments ranged from 27 KHz to 40 KHz. These reduced frequency responses will limit the operating range of this demonstration shaft monitoring system to about 140,000 rpm.

In order to test the shaft position analyzer on a rotating system, two general purpose calibrating fiberoptic deflectometers were positioned orthogonally to the surface pattern on a target titanium disk on a lab rotating demonstrator (see Figure 7).

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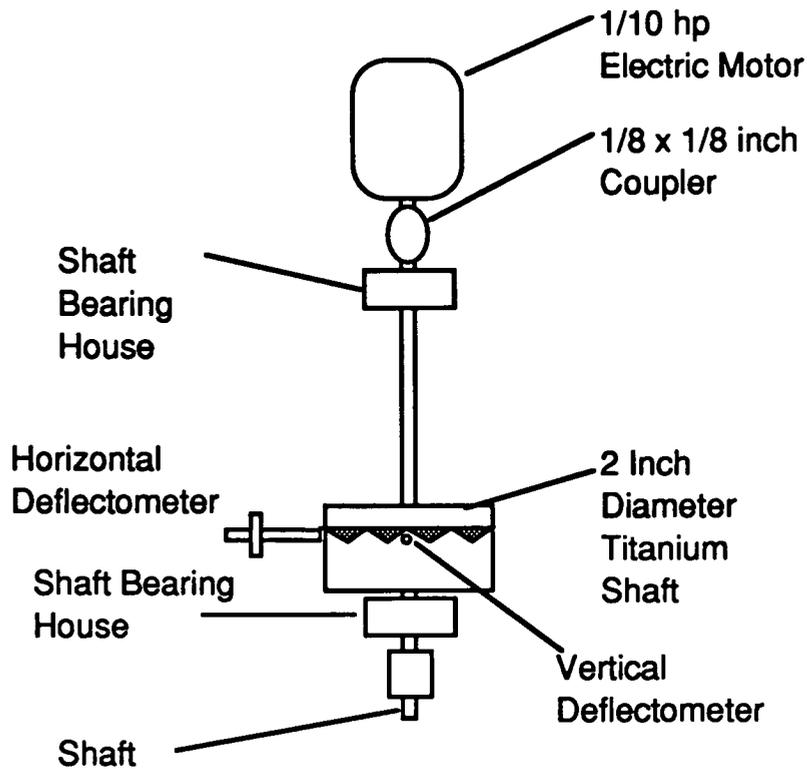
Figure 7   Rotating demonstrator schematic hardware configuration

The radial displacement of the disk was measured over a 15 mil range with a deflectometer which was signal processed by the analyzer (see Figure 8). The standoff distance between the deflectometer probe tip and the target surface was 40 mils. The linearity of the data is quite good, and a 8.72 microvolts/ micro-inch signal was measured. Although only 15 mils of radial motion were tested in this program, the overall radial range expected is based upon the calibration curve of the deflectometers used; thus, for our instruments, an overall range of about 50 mils of radial motion is expected.

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RADIAL DISPLACEMENT
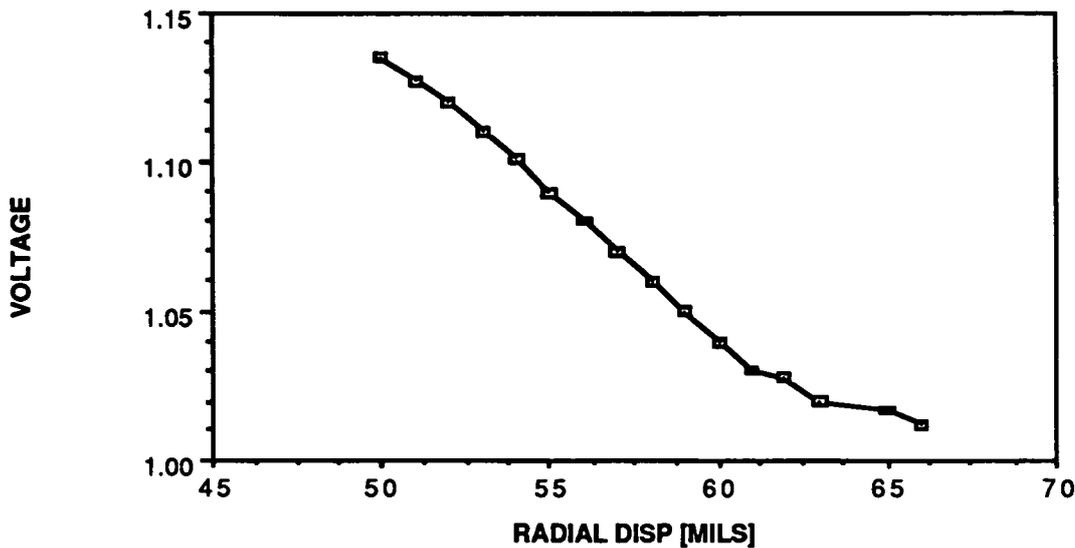
Figure 8

The ability of the analyzer to measure axial displacement was tested and found to be very sensitive to the pattern on the shaft. The pattern, as described above, consists of eight identical triangles placed end to end. The deflectometer responds to the AC change in reflectivity of the pattern as the disk rotates. The analyzer then converts the timing information to a DC signal proportional to axial displacement. If the triangles were uniform and the edges clean and precise, the output from the analyzer would be a simple DC signal. However, the triangles were not perfectly uniform, and they did not have clean and precisely straight edges. The result was that each triangle generated an individual DC level which showed non-linearity in output as the change in axial position resulted in a change in edge location relative to the optical probe. Thus, rather than being an unambiguous DC, the signal was an eight-level staircase representing each of the eight triangles. Even though our target edges were quite ragged, it was possible to compensate for the irregularity by averaging the voltage for each mil of displacement for each of the eight triangles to produce an average voltage for axial displacement. This simple technique resulted in a signal curve that was quite linear over the 10 mil range tested. The probe standoff distance was 40 mils and the axial displacement was measured within 0.34 mils (see Figure 9). Higher precision can easily be obtained by known signal conditioning techniques with a computer. Although only 10 mils of range was tested in this program, the overall axial range expected is based on the dimensional relationship between the probe and triangle sizes; in this case better than 30 mils of axial shaft motion.

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AVERAGED AXIAL DISPLACMENT
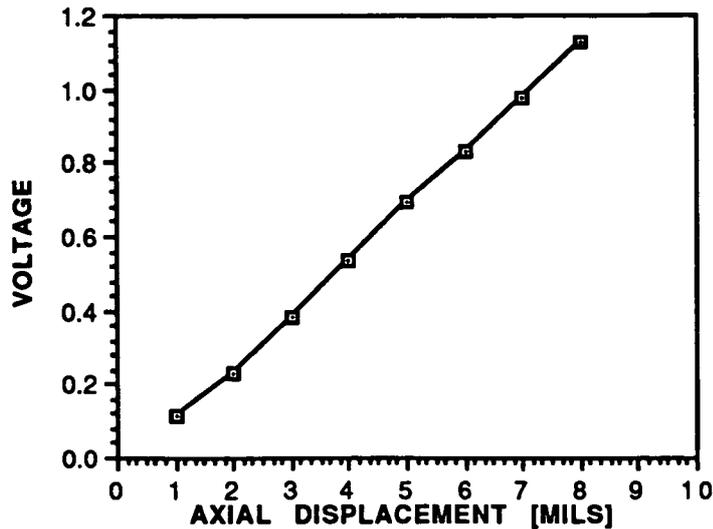
Figure 9

Program financial constraints restricted our test capability to a small 10,000 rpm benchtop test fixture. Nevertheless, it is possible to estimate the probable shaft monitor performance at the higher target rpm by extrapolation of the results from the benchtop tester.

The starting specification for the deflectometers was selected so that the time of flight of the surface being measured (i.e., shaft surface velocity) was matched to the time constant of the optical detector when the shaft is at 200,000 rpm. However, since the delivered sensor response performance is reduced from the starting specification by a factor of about two-thirds, the maximum shaft speed limit will also be reduced by a similar amount (with 140,000 rpm being the new expected limit for the system).

The deflectometer provides a constant output response as long as the shaft surface velocity is such that the sensing zone (a .063 inch spot through which the shaft surface is moving) sees an area of constant level (all dark, or all shiny) for a time that is at least as long as the sensor response time. Thus, our fiberoptic detector output should provide a flat response up to about 58,000 rpm (instead of 92,000 rpm as originally specified). As the shaft speed increases upwards to about 92,000 rpm (instead of 150,000 rpm as originally specified), surface velocity through the sensing zone increases until the detector has insufficient time to see only an area of constant level; all level determinations become contaminated enough by leftover measurement from the previous level (i.e., dark or shiny) that the measurement precision starts to be affected. This process continues up to 140,000 rpm (instead of 200,000 rpm), where the transition time across the whole target triangle is equal to the detector response time; this point is the 3db half power limit of the sensor.

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The slight degradation in sensor precision described above should have only a small effect on the radial measurement, and probably will be unnoticeable in its effect on the axial measurement. The analyzer signal conditioner includes circuitry that interpolates points between measurements and synthesizes additional measurements to improve the processor sampling statistics; this also smooths the apparent continuity of motion in shaft measurements. One of the effects of this provision is to maintain the radial motion sensitivity of the shaft monitor, with only a slight sacrifice in precision. The slight decrease in precision becomes advantageous for axial motion determination since it diminishes the sensitivity to non-uniformity in the target edges.

A data display and plotting code compatible with the output of this analyzer has been developed under another project that will allow test engineers to accumulate and display a time history plot of the shaft orbital motion data from this system during use in tests.

Future Issues

Some of the main issues that will need to be addressed in the future include compensation for two-phase flow perturbations, issues concerning pattern quality and placement on the shaft, alterations in the target surface reflectance after installation, and computer interfacing. These subjects are discussed in the following paragraphs.

Wherever possible, the measurement environment where optic sensors are to be used should be designed so that two-phase flow is not present. If optical sensors must be used in an environment where bubbles can occur in the fluid media, the signal data can be perturbed by random occlusion of the light path as the bubbles pass between the fiberoptic sensor and the target surface. These occlusions would be manifested as sudden decrease events in light intensity which could confuse the processing electronics in the analyzer. Some immunity to the effects of the perturbations could be acquired by phaselock loop tracking and signal gating, by signal conditioning with pattern recognition to exclude questionable data, and by the addition of sensors to provide "voting" capability so that data that is not coherent with shaft motion is excluded.

The shaft monitor is sensitive to target pattern irregularity, edge roughness, and surface finish. Increased precision in target uniformity can be achieved by careful development of the target stencil or mask so that all of the triangles are precisely uniform. A large-scale drawing can be produced on a drafting computer, and photographically reduced to the dimensions needed for the shaft surface treatment mask stencil. Better methods need to be developed for copying the stencil onto a media that can serve as a mask for the selected surface treatment. Outlining the target triangle edges with a machined scribe line might increase the sharpness in the demarcation edge between the dark and the shiny areas of the target; this could substantially improve the axial motion measurement precision, although it might introduce reflectance

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variables that would need to be processed out. Surface finish of the target area must be polished to a roughness level that is less than the minimum detectable distance increment. For most applications a finish of about ± 10 micro-inches insures that surface irregularities will not interfere with the measurement. Where high radial motion precision is needed, a finish of ±2 micro-inches may be desirable.

Degradation of the finished (shiny) surfaces may occur due to oxidation by the fluid media, contamination with solvent residues, and from dirt or oil from handling. Mechanical scratching of the high finish surfaces can degrade the reflectance significantly. This commonly occurs during shaft installation by scraping against other components or by rough handling. The finish can also be seriously degraded by misguided attempts at polishing with inappropriate tissues and cloth; once the finish is prepared, it should only be touched with optical grade lens tissue, and even then with extreme care. Finally, one of the most common sources of scratching and gouging of the target finish is from direct contact with the deflectometer probe face, especially during calibration.

Many of the adjustment and calibration features of this instrument system are inefficient and difficult, and should be managed by a computer interface module. Such an interface would be modelled on our previous similar processing controllers, and should not prove difficult or expensive to construct. The typical approach would include provisions for data acquisition on all channels, and special processing for pattern recognition, and shaft clocking.

Conclusions

The shaft position analyzer has been successfully developed to measure shaft speed, shaft axial and shaft radial displacement with a pair of optical sensors. Laboratory tests demonstrated the system operates up to measurement expectations in a tester at speeds up to 10,000 rpm. The optical sensors have been constructed for use in a 200,000 rpm LH_2 environment, and, except for probe pressure environment leak checks which will be done in the near future, the system is ready for use in its targeted turbomachinery tests.

Recommendations for Future Technology Development

1. The next development stage for the shaft analyzer system would be the inclusion of a computer interface to allow direct interaction between the analyzer and a data storage/analysis/display computer.

2. Develop alternative methods of low-cost fiber metallization and soldering (or brazing) leading to a relatively inexpensive off-the-shelf fiber bundle methodology that would reduce deflectometer costs in cryogenic turbopump test applications.

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15. Supplementary Notes

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16. Abstract

Recent work has been carried out on development optical technology to provide real time monitoring of shaft speed, shaft axial displacement and shaft orbit of the OTVE hydrostatic bearing tester. Results show shaft axial displacement can be optically measured (at the same time as shaft orbital motion and speed) to within 0.3 mills by two fiberoptic deflectometers. This paper presents the final results of this condition monitoring development effort

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