2-7-91
E5892

NASA Technical Memorandum 103676

Rotating Pressure Measurement System Using an On Board Calibration Standard

Richard G. Senyitko and Philip Z. Blumenthal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Robert J. Freedman
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Prepared for the
37th International Instrumentation Symposium
sponsored by the Instrument Society of America
San Diego, California, May 5–9, 1991

NASA

ROTATING PRESSURE MEASUREMENT SYSTEM USING AN ON BOARD CALIBRATION STANDARD

Richard G. Senyitko Philip Z. Blumenthal
Robert S. Freedman

ABSTRACT

A computer-controlled multichannel pressure measurement system has been developed to acquire detailed flow field measurements on board the Large Low Speed Centrifugal Compressor Research Facility at the NASA Lewis Research Center. A pneumatic slip ring seal assembly is used to transfer calibration pressures to a reference standard transducer on board the compressor rotor in order to measure very low differential pressures with the high accuracy required. A unique data acquisition system was designed and built to convert the analog signal from the reference transducer to the variable frequency required by the multichannel pressure measurement system and also to provide an output for temperature control of the reference transducer. The system also monitors changes in test cell barometric pressure and rotating seal leakage and provides an on screen warning to the operator if limits are exceeded. This paper discusses the methods used for the selection and testing of the reference transducer and describes the data acquisition system hardware and software design. The calculated and experimental data for the system measurement accuracy are also presented.

INTRODUCTION

The Large Low Speed Centrifugal Compressor facility (Ref. 1) at the NASA Lewis Research Center (LeRC) was designed and built in an effort to improve the performance of small gas turbine engines by obtaining benchmark experimental data for internal flow code verification and modeling. As illustrated in Figure 1, the 1.52 m (5 ft) diameter compressor rotor is driven by a 1500 hp variable speed electric motor and gear reducer to a design speed of 1920 rpm. Outside air, at flow rates up to 45 kg/sec (100 lb/sec), enters the research facility through a roof vent containing louvers and steam pipes for temperature control and is drawn into the plenum through a bank of flow straighteners. The air then passes through a bellmouth with a 10:1 area contraction, flows through the 1.18 pressure ratio compressor, and exits through a throttle valve at the entrance to the collector. The air is then discharged into an altitude exhaust line capable of providing 26 in. of vacuum at the maximum flow rate.

A variety of instrumentation and measurement systems is used to acquire research data on the rig. This includes aerodynamic survey probes, strain gages, thermocouples, clearance probes, and a shaft torquemeter. In addition, high quality glass windows are provided in several regions to allow use of a laser velocimeter and flow visualization techniques such as ammonia ozalid, fluorescing oil, liquid crystal, and tufts. The compressor rotor is also heavily instrumented with 252 static and total pressure taps at 10 different planes in the throughflow direction and 18 static pressure taps on the spinner. Because the rotor operates at relatively low speeds, the pressure differentials from hub to shroud vary from about 0.0145 psi to 0.7 psi, with differences between pressure taps as small as 0.001 psi. The method chosen to meet the research requirements for high accuracy measurement of these pressures was to provide an Electronically Scanned Pressure (ESP) system on board the rotor.

ESP SYSTEM DESCRIPTION

The ESP measurement system that was chosen had been used for tests in other LeRC aeronautics facilities in the past with a great deal of success. The system utilizes miniature modules each containing 48 silicon piezoresistive pressure sensors, a pneumatic calibration valve, and electronics for addressing and amplifying each sensor. Five ESP modules are mounted on the rotor centerline on an instrumentation tower (Figure 2) which is located under the rotor nose cone. The transducer diaphragms within the modules are oriented perpendicular to the centerline to minimize rotational acceleration effects. A 200 channel slip ring package is used to bring the electrical signals from these modules plus on board strain gages, thermocouples, heaters, and other items to the data acquisition systems. The transducers are addressed and scanned at the rate of 10 000 measurements per second.

The module calibration valve allows for on-line correction of transducer errors due to temperature changes, reference pressure changes, and electrical drift. When a 100 psi control pressure is applied, the valve manifolds all transducers to a calibration system which applies three known pressures (measured by a reference transducer) in succession to all transducers. At each calibration pressure the transducers are scanned and a second order curve is generated for each transducer. This information is stored in the ESP system memory and is used to convert the transducer voltages to absolute engineering units (psia).

Since all the transducers in the ESP module are differential, the backsides of the diaphragms are manifolded internally to a reference pressure port. Ambient barometric pressure is used for this reference to avoid bringing a stable pressure on board the rotating system. The test cell ambient barometric pressure is monitored by a high accuracy digital barometer.

PNEUMATIC SEAL OPERATION

A pneumatic slip ring seal assembly (Figure 3(a)) was designed and built to transfer the control and calibration pressures from the stationary pressure calibration unit to the rotating ESP system. Although the pneumatic seal assembly functioned per design specifications, its leak rate was not low enough to meet the accuracy required for in-place calibration of the rotating ESP system. This leakage in the rotating seal caused the calibration pressures seen at the ESP modules to differ from the pressures measured by the reference transducer in the calibration unit. This made it necessary to install the reference transducer on board the rotor in close proximity to the sensor modules. This provided high accuracy measurement of the three calibration pressures as long as the seal leak rate did not change during the calibration cycle.

Another problem was that excessive heat (approximately 350 °F in the area of the instrument tower) was produced within the pneumatic seal assembly by the friction of carbon rings rubbing on stainless steel runners (Figure 3(b)). The original seal design had provisions for seven individual chambers for transferring pressures to the rotor. Three chambers were the minimum required for performing the on-line calibrations (two chambers for the control pressures and one chamber for the calibration pressures). In an attempt to reduce the heat generated, the hardware was removed from four of the seven chambers and cooling air was fed through the four empty chambers. Also the two ESP pneumatic valve control pressures for calibration and run positions (approximately 100 psi each) were applied for only a short time (5 sec) in order that the carbon rings would not be forced into the stainless steel runners for more time than was necessary. This reduced the temperatures in the area of the rotating ESP system to less than 170 °F. However, this change from ambient temperature at zero speed to 170 °F at design speed could still cause a change in the output of the measurement transducers and reference transducer which would degrade overall system accuracy.

REFERENCE TRANSDUCER SELECTION

One transducer that was chosen as a candidate for measuring the calibration pressures on board the rotor was the digital pressure transducer normally used with the ESP system (Ref. 2). This transducer uses a quartz crystal oscillating beam as its sensing element. Pressure applied to a bellows generates a torque and force about a pivot point. This in turn changes the force on a suspended quartz beam, thus changing its resonant frequency. This frequency is converted to a pressure measurement via a second order relationship. The manufacturer's specifications for this transducer are as follows:

Repeatibility: 0.005% F.S.

Hysteresis: 0.005% F.S.

Six month stability: 0.008% F.S.

Accuracy: ±0. 01% F.S.

The other candidate transducer was an analog pressure transducer whose physical characteristics were suitable for the rotating pressure measurement system. This transducer uses a variable-capacitance ceramic sensor which deforms proportionally to applied pressure (Ref. 3). Gold electrodes on the inside surfaces of the ceramic sensor move closer to each other when pressure is applied, increasing the capacitance. The capacitance is converted to a linear dc signal via a circuit utilizing a charge balance principle. The specifications for this transducer are as follows:

Repeatibility: 0.01% F.S.

Hysteresis: 0.01% F.S.

Six month stability: 0.1% F.S.

Accuracy: ±0. 05% F.S.

ROTATIONAL EFFECTS

A spin rig was used to conduct individual tests on each of the system components to determine effects from angular acceleration due to rotation. The effect of rotation on the sensors in the ESP modules was negligible. The output of the digital pressure transducer changed beyond its accuracy specification as it was rotated. The change in the analog pressure transducer output due to rotation stayed within the transducer accuracy specification.

THERMAL EFFECTS

Despite the attempts made to cool the pneumatic seal assembly, the rotating ESP system would still be exposed to temperatures as high as 170 °F during research testing. Identification of possible thermal effects on the system components was done in a temperature controlled chamber.

To determine the null thermal shift on the sensor modules, one measurement transducer on each sensor module had the same pressure applied to both sides so that any changes in its output would be because of a temperature change and not because of changes in its reference pressure. It was found that the output of the measurement transducers on the sensor modules shifted significantly as temperature changed and the amount of shift was different for each transducer. This shift can be minimized if the ESP system is recalibrated frequently.

When the digital pressure transducer was tested in the temperature controlled chamber, it was found that its output was extremely sensitive to temperature changes and had a long settling time (Figure 4) making it impractical for use in the rotating ESP system.

The analog pressure transducer was tested in the same manner. The tests showed that only rapid changes in temperature affected the output of the transducer (Figure 5). By keeping the transducer at a temperature slightly above the highest temperature it would be exposed to during a test (170 °F), any effects caused by temperature would be minimized. It was decided that this transducer would be best suited for the rotating ESP system despite its lower accuracy specification. The transducer temperature was maintained at 170 °F by a closed loop PID controller regulating a heater mounted on the transducer. The heater was also equipped with over-temperature protection.

DC TO FREQUENCY CONVERSION

Since the ESP system was designed to use only the digital pressure transducer, the 0- to 5-V signal from the analog pressure transducer had to be converted to a 36- to 40-kHz, 4-V p-p, square wave so the system could interpret it. A system was designed to convert the analog signal to a frequency without significantly affecting the accuracy. The system consisted of a programmable frequency generator (PFG), a digital voltmeter (DVM), and a data acquisition and control system (DACS) (Figure 6). Communication among these three instruments was accomplished via an IEEE-488 bus with the DACS acting as the bus controller. When the system is in operation, the DACS reads the transducer signal through the digital voltmeter and instructs the frequency generator to output the appropriate frequency to the ESP system (Figure 7). In the event of a DACS failure, a watchdog timer will activate an alarm.

DACS PROGRAM

A flowchart for the program that operates the system is shown in Figure 8. The program performs the following functions:

- Reads the transducer analog output from the DVM via IEEE-488, converts it to pressure units (psia), converts pressure units to a frequency value, and outputs this frequency value via IEEE-488 to the frequency generator.

- Monitors the transducer output for fluctuations outside a specified range which would indicate a possible pneumatic seal leakage problem. This feature is disabled during calibration of the ESP system because the three different calibration pressures applied would be interpreted as a pneumatic seal problem.

- Monitors the test cell barometric pressure for changes. Since the test cell barometric pressure is used as the reference pressure for the sensor modules, a change in this pressure would necessitate an online recalibration of the rotating ESP system to maintain the best accuracy.

- Reads the transducer temperature and converts it to a 1-to 5-V control signal that is outputted to the PID heater controller which controls the transducer temperature.

- Alerts the operator with an on-screen warning if either the analog transducer output or barometric pressure changes beyond their specified limits.

LINEARIZATION EQUATION

The equation used by the ESP system to convert the digital pressure transducer output into engineering units expressed in psia is as follows (Ref. 4):

$$P = A(1 - t_0/t) - B(1 - t_0/t)^2$$

where

P = pressure in units of A and B (psia).

t_0 = period of the digital transducer output at 0 psia in microseconds.

t = measured period of the digital transducer output in microseconds.

To apply the linearization equation, the calibration coefficients, A, B, and t_0 must be known.

The following information is supplied by the manufacturers:

- The digital transducer output frequency at 0 psia (f_0) is 40 kHz.

- The digital transducer output frequency at full scale (f) is 36 kHz.

- Full scale pressure for the analog transducer is 20 psia.

Since $t = 1/f$, the equation becomes:

$$P = A(1 - f/f_0) - B(1 - f/f_0)^2$$

Since the analog transducer output is linear,

$$B(1 - f/f_0)^2 = 0 \text{ so } B = O$$

The equation simplifies to:

$$P = A(1 - f/f_0)$$

Substituting: $P = 20$ psia, $f = 36$ kHz, and $f_0 = 40$ kHz:

$$20 = A(1\text{-}36/40)$$

$$A = 200$$

Calculate t_0:

$$t_0 = 1/f_0 = 1/40\ 000$$

$$t_0 = 25\text{x}10^{-6}$$

Summarizing:

$$A = 200 \text{ psia}$$

$$B = 0 \text{ psia}$$

$$t_0 = 25\ \mu\text{s}$$

Using these three coefficients, the byte values can be generated using the standard method and input to the ESP system so the signal from the frequency generator (which represents the analog transducer output) can be interpreted as a pressure.

SYSTEM ACCURACY

The accuracy of the system is as follows (Note: The digital voltmeter and frequency generator accuracies have been converted to "psi" for tabulation purposes.):

- Analog transducer accuracy: ±0.05% F.S.

  (F.S. = 20 psia) ±0.010 psi

- Digital voltmeter accuracy: ±0.005% input + 100 μV

  (Input = 5.0 V @ 20 psia) ±0.0014 psi

- Frequency generator accuracy: ±0.0001 Hz

  (4000 Hz = 20 psia) ±0.000005 psi

- ESP system accuracy (less above accuracies): ±0.005 psi

The accuracy of the entire rotating calibration pressure measurement system was calculated to be ±0.0101 psi using the root sum squared (RSS) method. The limiting factor for the total system accuracy is the analog transducer accuracy (±0.010 psi). The accuracy of the entire ESP system was calculated to be ±0.015 psi.

EXPERIMENTAL RESULTS

The accuracy of the entire rotating calibration pressure measurement system was verified under actual operating conditions. The pressure port of the analog transducer on board the rotor was connected to a total pressure probe which was mounted off the front of the spinner. A highly accurate (±0.004 psi) 20 psia digital pressure gage was mounted off the rig and connected to a total pressure probe inside the plenum (which is upstream of the spinner). The pressure at both locations should be the same because both probes are in the free stream far enough from the walls of the inlet so boundary layer effects are negligible. The analog transducer on board the rotor was compared to the digital pressure gage under rig design operating conditions. Several tests were conducted to ensure repeatability. The results of these tests showed that just after reaching design conditions, the two readings differed by 0.009 psi and after 1 hour the two readings were the same. Immediately after the rig was shut down, the readings differed by 0.003 psi and after 10 minutes the readings were the same again. The two readings tracked the air flow rate through the facility (Figure 9).

Based on the calculated and experimental results, it can be concluded that the accuracy of the rotating calibration pressure measurement system is ±0.010 psi. Thus the accuracy of the entire rotating ESP system would be the sum of the manufacturer's specified system accuracy (±0.005 psi) and the experimental accuracy of the rotating calibration pressure measurement system (±0.010 psi) or ±0.015 psi.

CONCLUSION

Aeronautics research at the NASA Lewis Research Center has relied heavily on the accurate measurement of pressures on engine components to design more efficient engines. Acquisition of these pressure measurements on stationary components is accomplished with proven techniques and methods. Measuring pressures on rotating components is difficult because of possible rotational and thermal effects as well as operational problems. The rotating ESP system on board the Large Low Speed Centrifugal Compressor at the NASA Lewis Research Center has provided researchers with data that could not have otherwise been obtained. The system has proved to be a valuable tool in understanding the complex flow phenomena existing in the blade passages of the Large Low Speed Centrifugal Compressor. The system is also targeted for use on a Large Low Speed Axial Compressor at the NASA Lewis Research Center in the early 1990s.

REFERENCES

1. Wood, J.R., Adam, P.W., and Buggele, A.E., "NASA Low-Speed Centrifugal Compressor For Fundamental Research," NASA TM-83398, June 1983.

2. Paros, J.M., "Digital Pressure Transducers," Paroscientific, Inc., reprinted from Measurements & Data, Vol. 10, No. 2, Issue 56, Mar.-Apr. 1976.

3. Setra Systems Model 270 Specification Sheet, Setra Systems Inc., January 1990

4. Paroscientific, Inc., "Calculation of Pressure From Calibration Coefficients," pp. 2-3, May 1981.

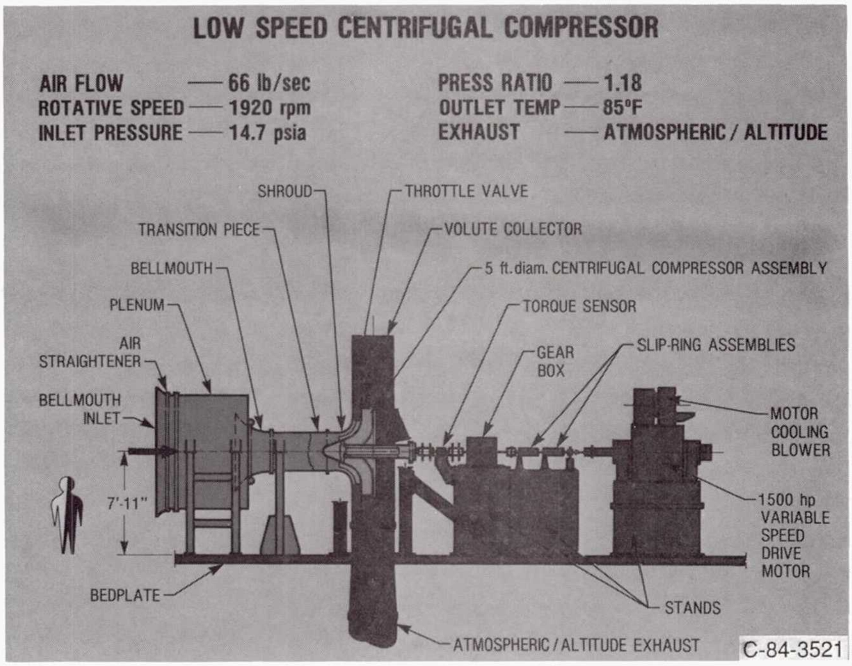


Figure 1.—Large low-speed centrifugal compressor facility.

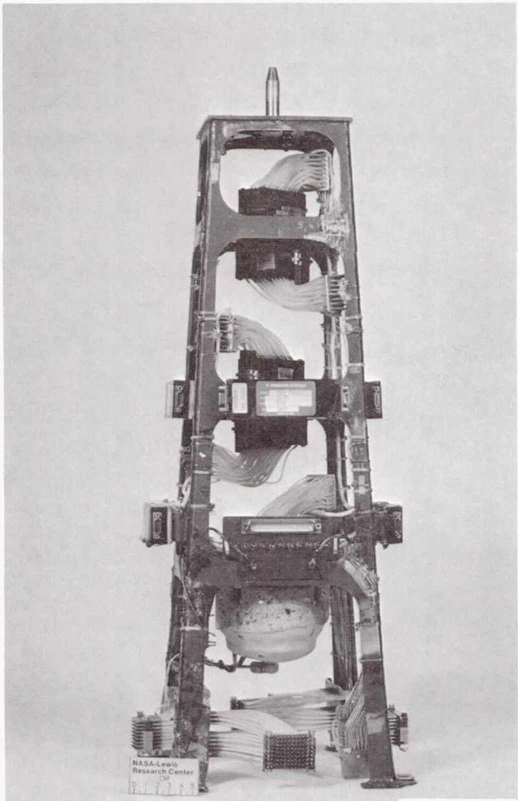
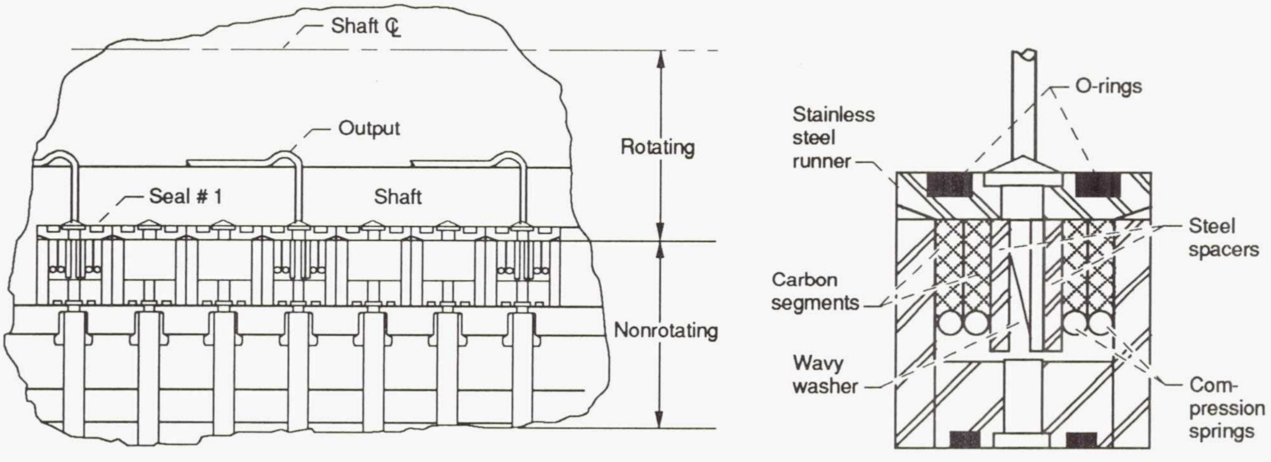


Figure 2.—Instrumentation tower.



(a) Assembly.

(b) Detail.

Figure 3.—Pneumatic slip ring seal assembly.

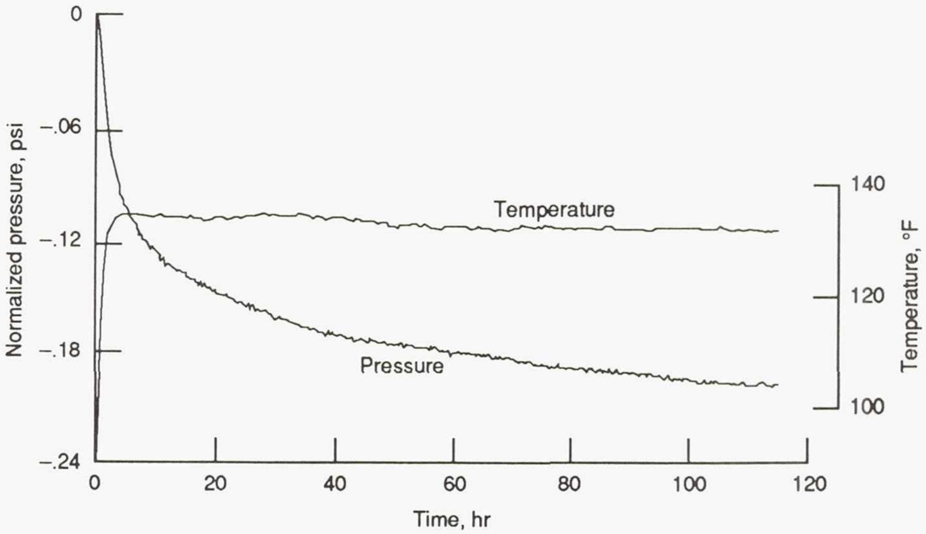


Figure 4.—Digital transducer thermal effects.

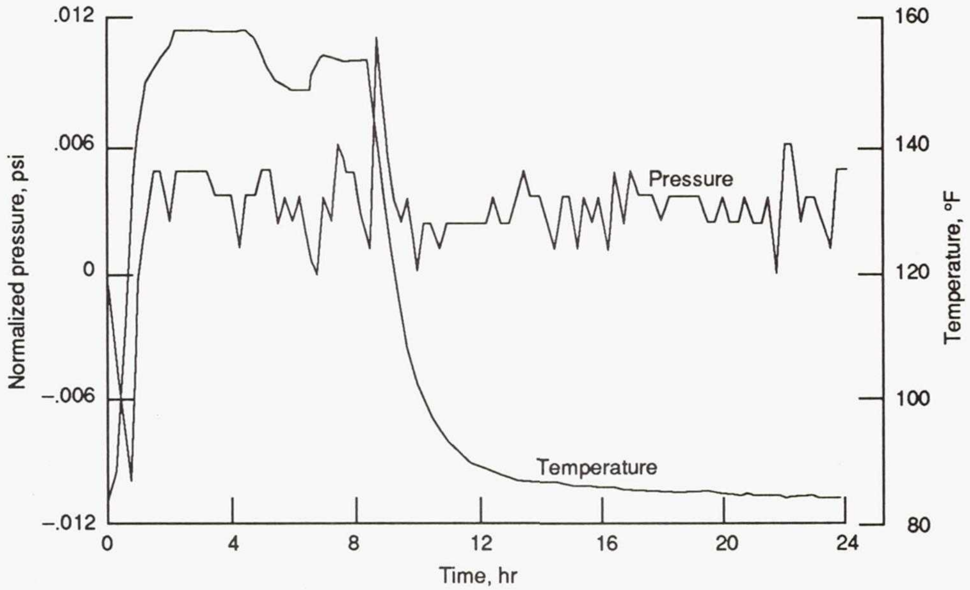


Figure 5.—Analog transducer thermal effects.

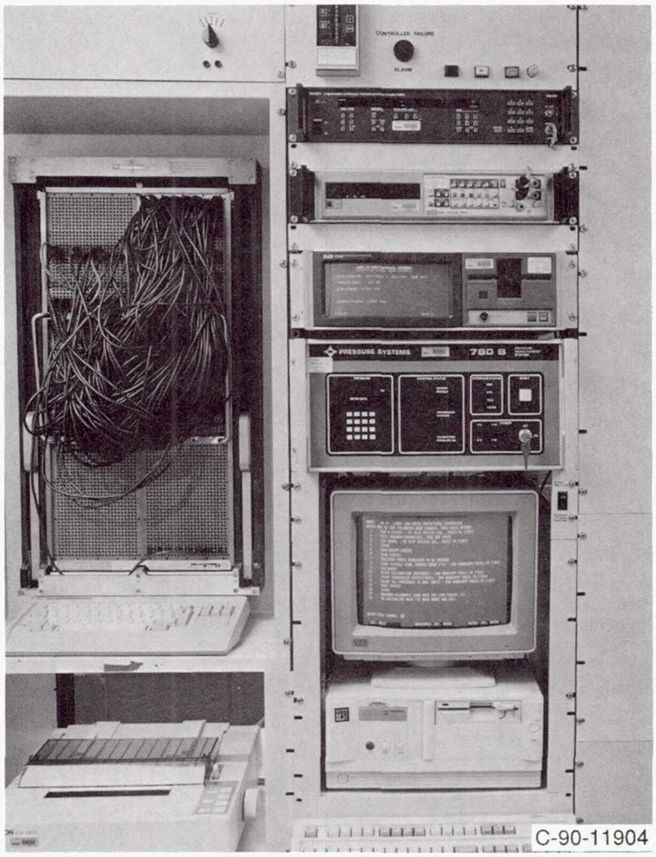


Figure 6.—ESP data acquisition system.

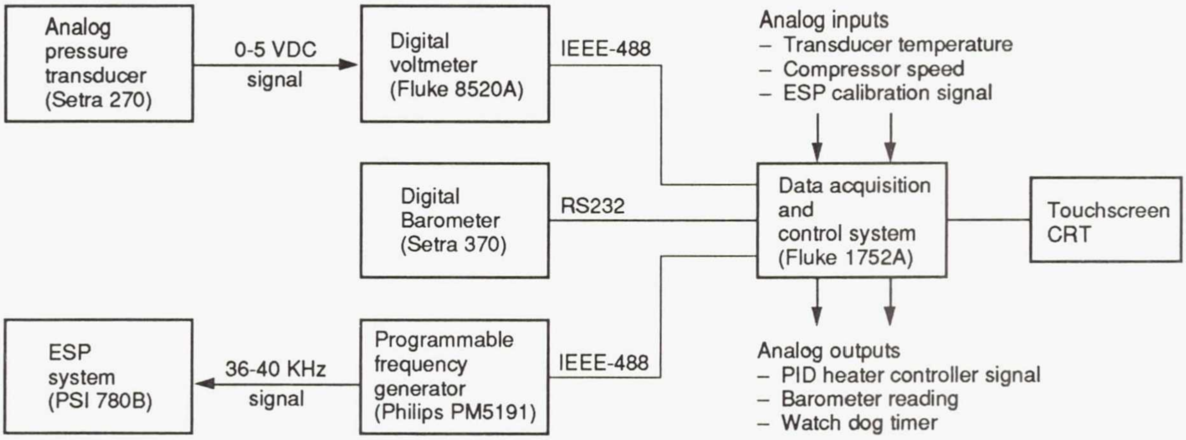


Figure 7.—Instrument system block diagram.

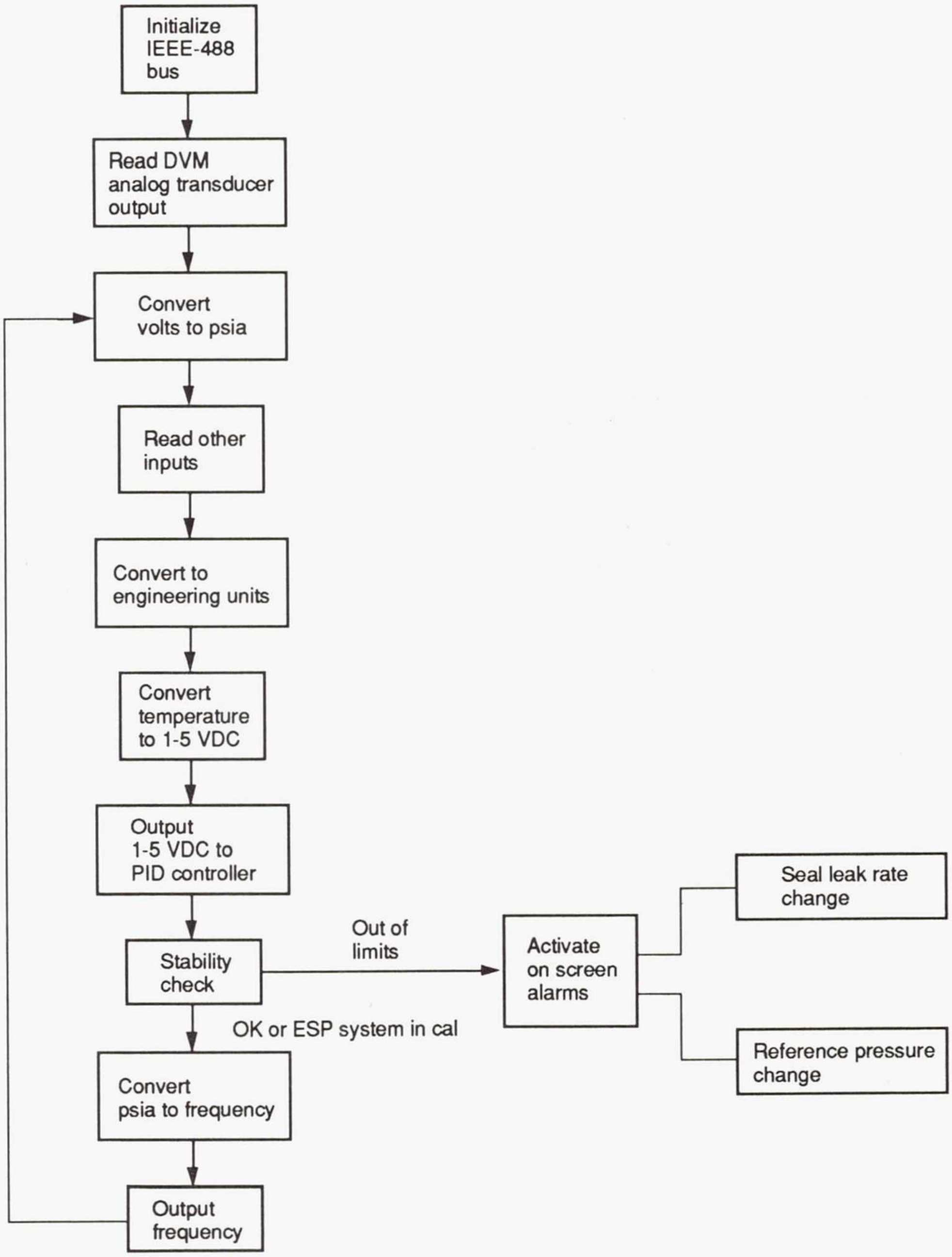


Figure 8.—DACS program flow chart.

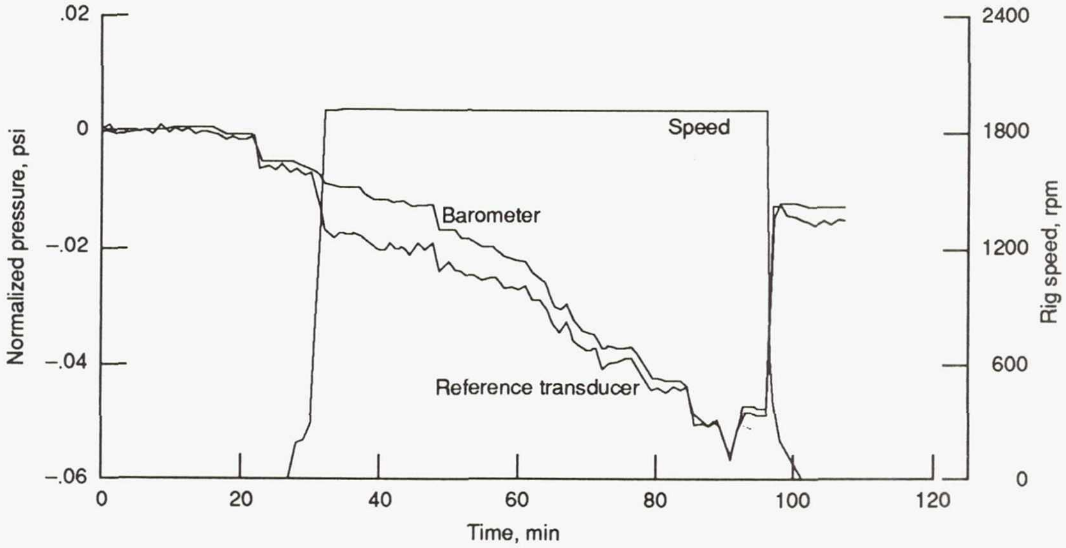


Figure 9.—Reference transducer accuracy test.

NASA
National Aeronautics and
Space Administration

Report Documentation Page

1. Report No.
NASA TM-103676

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Rotating Pressure Measurement System Using an On Board Calibration Standard

5. Report Date

6. Performing Organization Code

7. Author(s)
Richard G. Senyitko, Philip Z. Blumenthal, and Robert J. Freedman

8. Performing Organization Report No.
E-5892

10. Work Unit No.
505-62-84

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the 37th International Instrumentation Symposium sponsored by the Instrument Society of America, San Diego, California, May 5-9, 1991. Richard G. Senyitko and Philip Z. Blumenthal, Sverdrup Technology, Inc., Lewis Research Center Group, Brook Park, Ohio 44142. Robert J. Freedman, Lewis Research Center. Responsible individual, Richard G. Senyitko, (216) 433-2972.

16. Abstract

A computer-controlled multichannel pressure measurement system has been developed to acquire detailed flow field measurements on board the Large Low Speed Centrifugal Compressor Research Facility at the NASA Lewis Research Center. A pneumatic slip ring seal assembly is used to transfer calibration pressures to a reference standard transducer on board the compressor rotor in order to measure very low differential pressures with the high accuracy required. A unique data acquisition system was designed and built to convert the analog signal from the reference transducer to the variable frequency required by the multichannel pressure measurement system and also to provide an output for temperature control of the reference transducer. The system also monitors changes n test cell barometric pressure and rotating seal leakage and provides an on screen warning to the operator if limits are exceeded. This paper discusses the methods used for the selection and testing of the reference transducer and describes and the data acquisition system hardware and software design. The calculated and experimental data for the system measurement accuracy are also presented.

17. Key Words (Suggested by Author(s))
Compressors; Calibration; Data acquisition; Pressure instruments; Pressure sensors; Software

18. Distribution Statement
Unclassified – Unlimited
Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	14	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161