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A Digital Optical Torquemeter for High-Rotational Speed Applications

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SUMMARY

A digital optical torquemeter system designed for applications at high rotational speeds has been fabricated and tested for zero stability at speeds up to 20 000 rpm. Data obtained in a spin rig and with simulated inputs demonstrate that the system is capable of measuring torque bar twist to within 0.03° at speeds of 30 000 rpm. The optical system uses fiber optic bundles to transmit light to the torque bar and to silicon avalanche detectors. The system is microcomputer-based and provides measurements of average torque and torque as a function of angular shaft position. The torquemeter requires no bearings or other contact between the rotating torque bar and the nonrotating optics, and tolerates movement of the torque bar as large as 1 mm relative to the optics.

INTRODUCTION

To determine shaft torque in rotating machinery, a common technique is measurement of the twist in a torque bar inserted between the source and load. The torque bar is designed and calibrated statically for the desired torque range.

The use of strain gages mounted on the torque bar to measure twist becomes more difficult as the system rotational speed increases. The slip rings or telemetry used to transfer the strain gage outputs, the wire routing, and the gage application method are all potential problem areas in terms of cost, reliability, maintenance, and accuracy.

Optical methods for measuring the relative angle of twist across the torque bar have been developed and reported (refs. 1 to 4). This report describes an optical torquemeter with design features resulting in improved performance at high rotational speeds. The torquemeter measures the angle of twist by a method of pulse-time detection with digital signal processing. It differs from previous optical methods in that it:

(1) Has compensation for (limited) movement of the shaft relative to the stationary optical sensors, enabling contact-free (i.e., no bearings) operation between rotating and stationary parts,

(2) Is capable of measuring torque as a function of angular position of the shaft,

(3) Compensates for variations in optical source intensity and detector sensitivity,

(4) Has been tested to demonstrate torque measurement with less than 1 percent error at 20 000 rpm.

DESCRIPTION

The NASA torquemeter optics are shown schematically in figure 1. The torque shaft has a disk at each end. Six knife-edge tabs on each disk intercept the light beams at A,B,C,and D, and produce light pulses six times per shaft revolution. As torque is applied, the shaft twists to increase the angle of displacement, and thus the pulse-time difference between sensor pairs AB and CD. Torque is measured in duplicate by AB and CD. The pulse-time differences of AB and CD are converted to angle of shaft twist by digital angle clocks. Torque fluctuations can be measured with separate readings for each of the six tabs on the disk.

The optics at A,B,C, and D in figure 1 are attached to a common rigid base that holds all optical paths in one plane. As described in the next section, the base is permitted limited movement relative to the torque shaft. Thus, vibration and other forces produced by rotating parts of the test apparatus can be isolated from the optical unit by mounting the base to a bedplate. The optical system uses fiber optic bundles to transmit light to and from the torque bar flanges. Mirrors and lenses mounted within fixtures direct and focus the light beams in the plane of the flanges. Light path interruptions are detected by fast response silicon avalanche photodiodes capable of rise times of less than 100 ns.

The torque shaft can be replaced to change full-scale torque range as desired for test conditions. Possible errors caused by relative motion of the base and torque shaft are determined in the following section.

ERROR CAUSED BY RELATIVE MOTION BETWEEN TORQUE SHAFT AND OPTICAL UNIT

Relative motion of the torque shaft and optical unit consists of translation and rotation along and about axes x,y, and z in figure 1. Errors caused by any motion may be determined as an apparent angle of twist because the tab knife edges are radial, and the angle clock converts pulse time to shaft angle. The optical paths in figure 1 lie in one plane. With this condition the disk tabs always cut off the light in that plane. As a result there are only two principal sources of error for the sensor pairs AB and CD: rotation about the x axis, and translation along the z axis.

The error caused by rotation about the x axis is cancelled by combining the readings of AB with CD. The errors are of opposite sign, so the average of the readings from pairs AB and CD is the correct twist reading.

Translation along the z axis causes an increase in the light-spot diameter intercepted by the tab knife edge. At the focus the light-spot diameter is about 0.1 mm with a condensing lens with F-number of 3.3. This ratio causes an increased spot diameter of 0.1 mm for each additional 0.3 mm translation from the focal plane. A large light spot can change the light pulse shape and thus affect the pulse time determined by the electronic signal processor. When all four light spots at A,B,C, and D are initially focused on the plane of the tab knife edges, translation along the z axis increases the diameter of all four light spots the same amount. Perfect symmetry and averaging will cancel the torque error of AB and CD.

SYSTEM ELECTRONICS

The detector output (nominally 50 mV produced as each disk tab passes through a light spot) is shown as the input signal to a signal conditioner in figure 2. The signal conditioner produces a fast rise time pulse with digital logic compatible voltage levels. The pulse shaping scheme differs from typical fixed threshold level triggering in that the threshold level is a function (one-half) of the peak height of the detector output pulse. Therefore if, during operation, the detector sensitivity or the light intensity vary, the signal conditioner will continue to trigger at the same relative time position as illustrated in figure 2. The trigger point accuracy is of course still sensitive to signal-to-noise ratio at the detector output. The time-to-acquire-peak and the decay rate for the peak-sense-and-hold circuit are also shown in figure 2 and can be varied (although not independently) through component (capacitor) selection.

The overall electronics system block diagram appears in figure 3. The principle of operation is that the difference in time of occurrence between optical pulses B and A and between pulses D and C is measured by digital "angle" counters in units of angular movement. The measurements of individual pulse pairs are labeled by a tab counter. The measurement data with tab identifier are available for transfer to a microcomputer.

The angle clock generator is a digital system capable of generating a predetermined number of evenly-spaced output pulses (a clock waveform) based on the input time interval, which in this application is equal to one revolution period of the tab disk. The clock frequency can therefore be interpreted as an indicator of angular movement, hereafter referred to as "pulses/revolution." The angle generator has a rapid response time so that the output frequency is based on the previous one-revolution time period of the rotating disk. The stability of the rotational speed of the rotating hardware affects the angular accuracy; with a typical signal-to-noise ratio of the once-per-revolution sensor, an error in rotational speed of less than 0.1 percent is achievable. The angle generator also produces an auxiliary output frequency which can be set at a once-per-tab rate and can be used to index a tab counter as an identifier for each optical pulse pair. In this way torque variation as a function of tab angular position can be obtained if desired.

Digitally controlled delays are provided for the pulse 2 and 4 trains. The function of the delays is to ensure that the "angle" counters will measure the time difference between occurrences of the same tab at detectors A and B, and at detectors C and D. Since only positive "angle" can be measured, this delay can compensate for initial mechanical assembly and can also be increased to allow for a large negative angular displacement range (due to negative torque).

A timing diagram is shown in figure 4. The detector outputs (a) and (b) are shaped to waveforms (c) and (d). The pulse transitions corresponding to the tab knife-edges are acted upon in (e), where a digital delay can be added, (f), to ensure that the enable waveform (g) corresponds to the angle difference for the same tab. The once-per-revolution signal (h) from the rig generates (i) and (j) from the angle generator, and these signals, together with (g) provide the data valid (k) and counter-memory-load (l) signals. Since the data valid period for computer entry is dependent on relative time of occurrence between the generated once-per-tab signal and the corresponding optical pulses, the angle generator outputs can be (manually) positioned to maximize the data valid time prior to the arrival of pulses from the next pair of tabs.

A frequency-difference detector was added to the system as a safety device to monitor the integrity of the shaft-coupling joining the tab disks. A block diagram of the failure detector is shown is figure 5. The principle of operation is based on the comparison of pulse frequencies from the two tabbed disks with an alarm generated if the two frequencies differ by more than about 1 percent. Implementation of this technique uses frequency-to-voltage converters with voltage comparators to detect significant deviations. The time of response is about 50 ms.

The upper frequency limit of operation for the tested system is set by the digital delay counters. The limit is 7 MHz. At a shaft speed of 30 000 rpm, or 500 Hz, this frequency limit sets a nominal limit on the pulse rate of 12 000 pulses per revolution; 12 000 pulses per revolution corresponds to an inter-pulse period of 0.03°. This is the system's angular resolution. If full-scale torque causes an angular shaft deflection of 3°, for example, the torquemeter can measure the 30 K rpm full-scale torque to within 1.0 percent, using averaging if necessary where signal-to-noise ratios are low. At 10 000 rpm, the system resolution could be set as low as 0.01°, resulting in torque measurements to within 0.3 percent. Use of higher speed electronic counter components can of course increase system resolution at high rotational speeds. Also, elimination of digital delay counters in the tested system would allow operation at higher clock frequencies.

An integral part of the torquemeter system is a microcomputer and its two peripherals, a CRT terminal with hardcopy and a dual floppy disk storage system for programs. A digital panel meter display is also provided for average torque readings. The CRT terminal is used as a display device for individual measurement data for each tab and for each pair of detectors, and for averaged data. It also functions as the system control terminal. The disk system provides nonvolatile program storage and a medium for storing data for later analysis by the microcomputer. The microcomputer is also equipped with an IEEE 488 standard interface which can be used as a data transfer mechanism to large data acquisition systems. Figure 6 is a photo of the system electronics.

SYSTEM SOFTWARE

A detailed discussion of the microcomputer software programs developed for the optical torquemeter would not be of great benefit to the reader. A general discussion of the guidelines used in the software development follows in order to illustrate one possible implementation.

The operating programs used to calculate torque, display data, store data, and test the system electronics were written in a high-level computer language, BASIC. This language was chosen for its relative simplicity and for the ease of modification of programs written in BASIC. One disadvantage of BASIC in some applications is its slow speed of operation - in this application involving a steady-state measurement of torque, speed of computation is not critical and BASIC can be used satisfactorily.

The operating programs were written with several selectable modes of operation and display. The test operator can select:

(1) Display content from a choice of average torque, average torque for each tab, and average torque for each pair of detectors,

(2) Number of readings to average,

(3) Units from a choice of clock counts, angle in degrees, or ft-lb of torque.

The program utilizes a "zero torque" correction whereby initial mechanical offsets at zero torque conditions can be subtracted from each measurement. The zero values for each tab used by the program can be manually entered by the operator or can be calculated from the system data obtained under zero or near zero, torque conditions.

Higher speed programs were written to perform the actual transfer of data from the system clock counters and the tab counter to the computer, and torque data to the display panel. A few simple check functions such as verifying data availability and proper tab label, and the code conversion of data for display were written in computer "assembly" language. The performance of the software is the most important factor in judging its suitability in a given application of the torquemeter. The system software will provide a display of torque from an average of two readings of each of six tabs at a rate of about one update per sec. The system will display an output table of average torque, average torque at each tab location, and overall average for each detector pair, from an average of five readings of each tab, with an update about every 4 seconds. A data storage program was also written to record data blocks of up to 1000 readings each of the clock counters (for a random sequence of tabs) for later processing and display. This BASIC program stores readings at a rate of about 70 per sec. (1000 readings would therefore cover a period of 15 sec of run time.)

The torque bar calibration in units of ft-lb/deg and the system angle frequency in terms of pulses/revolution are entered by the operator when the program is initiated. At the same time, the operator selects the display mode, display units, and zero offset readings. The operator can update any of these parameters during the test by interrupting program performance through the use of a pushbutton switch which is "interrogated" by the computer after every display update.

CALIBRATION

The light pulses are detected and digitally processed to give the sum of displacement angle between the tabbed disks at zero torque plus the shaft angle of twist as torque is applied. To determine the angle at zero torque, the shaft is rotated at a low speed under conditions where the torque is small enough to be independently determined with acceptable accuracy.

Static calibration of torque against angle of twist is done with optical measurement of angle of twist by an autocollimator sighted on flat

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of + one count at one sensor pair was compensated by a - one count change at the second pair.)

SUMMARY

A digital optical torquemeter system designed for high rotational speed applications has been fabricated and then tested for zero stability at rotational speeds up to 20 000 rpm. The design features compensation for movement of the torque bar shaft relative to the optical sensors, with a movement of 1 mm in any direction resulting in an apparent torque bar angle of twist of less than 0.02°. Electronic compensation for variations in the optical path transmission is also provided.

The system uses an angle-referenced clock technique whereby the clock frequency is updated every shaft revolution such that the clock rate represents a selected number of pulses per revolution (nominally 12 000). The system digital counters therefore count increments of angle rather than increments of time, resulting in a measurement independent of gradual variations in rotational speed.

The system has been tested at actual shaft speeds from 2000 to 20 000 rpm and at simulated speeds of over 30 000 rpm. All data demonstrate that the system is capable of measuring torque-related twist to within 0.03° at these speeds.

The system uses fiber optics to transmit light from one halogen lamp and to return it to four fast response silicon avalanche detectors. A mirror/lens arrangement is used to focus the light beam to a 0.1 mm spot in the plane of beam-cutting knife-edge tabs.

The system is microcomputer based and has data reduction programs capable of providing output data in a variety of formats, including average torque in ft-lb or angle of twist, and torque as a function of shaft angular position. Displays are updated as rapidly as once per sec. Individual data samples are obtained about every 15 ms.

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3. Krsek, A.; and Tiefermann, M.: Optical Torquemeter for High Rotational Speeds. NASA TND-1437, 1962.

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TABLE I. - OPTICAL TORQUEMETER ZERO STABILITY DATA

rpm	Readings/tab	Output in counts (Resolution of one count ≡ 0.03°)		
		Sensor pair 1	Sensor pair 2	Average
5 000	1	-0.15	+0.07	-0.04
	4	-.15	+.28	+.06
	10	-.07	+.12	+.03
10 500	1	-.55	-.17	-.36
	4	-.30	-.08	-.19
	10	-.05	+.02	-.02
15 200	1	-.88	.00	-.44
	4	-.72	-.04	-.38
	10	-.90	+.13	-.38
20 000	1	-2.05	+.67	-.69
	4	-1.93	+.83	-.55
	10	-1.90	+.57	-.67

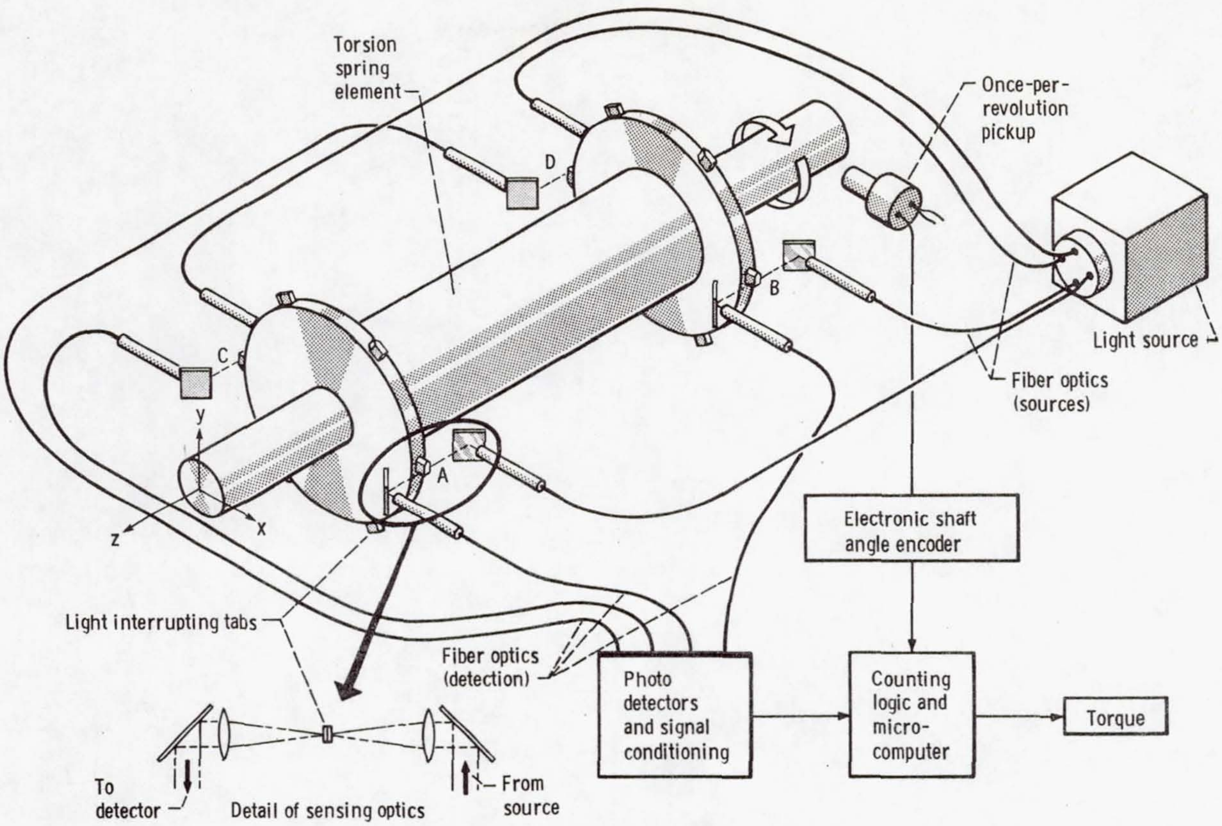

Figure 1. - Optical torquemeter system.

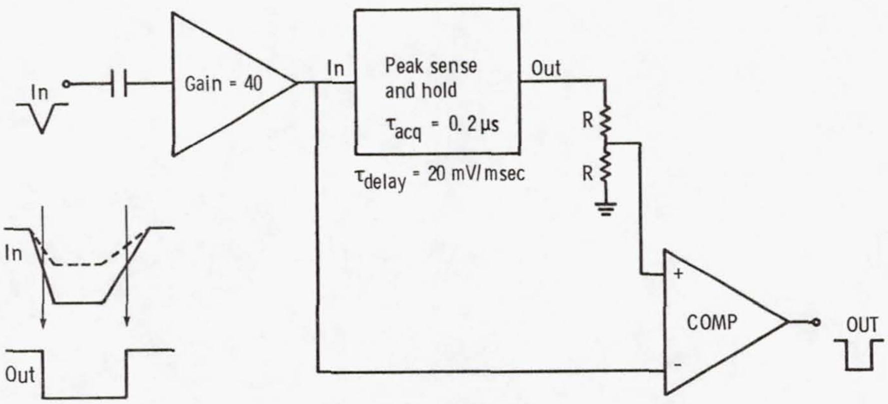

Figure 2. - Optical torquemeter signal conditioner block diagram.

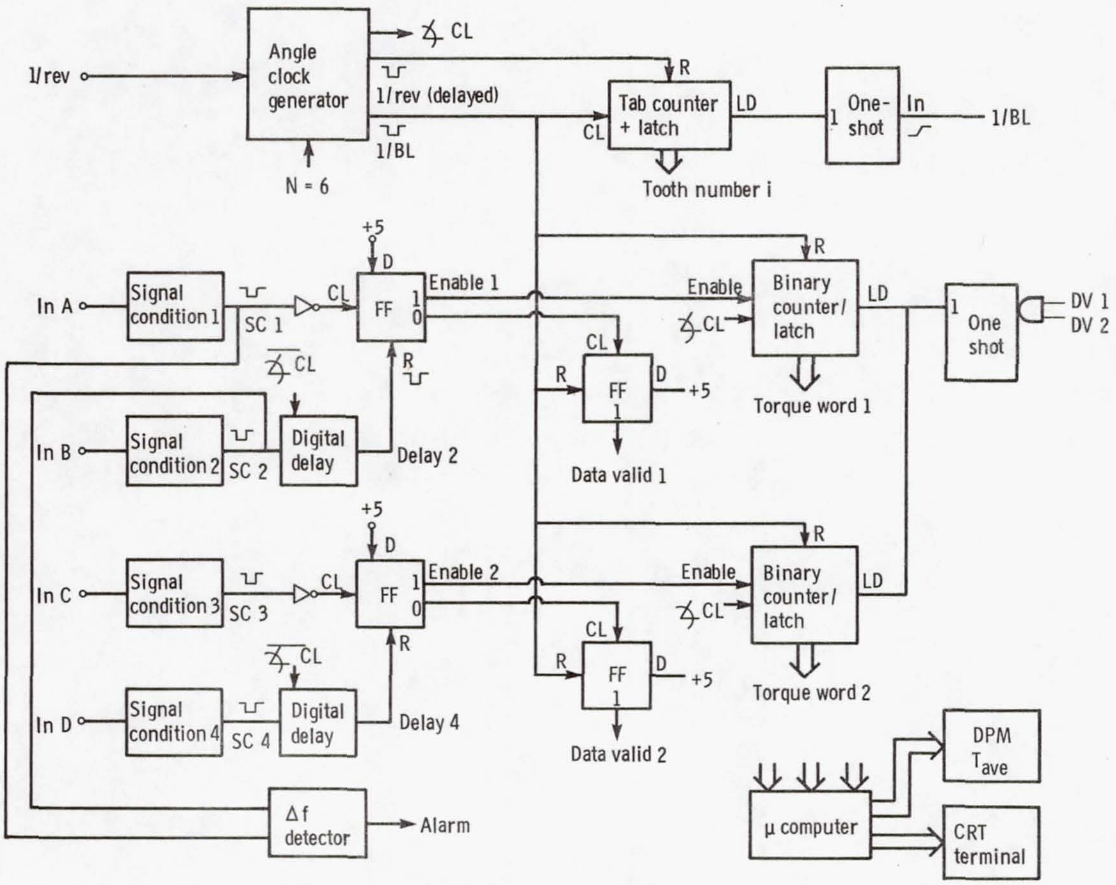

Figure 3. - Electronics block diagram.

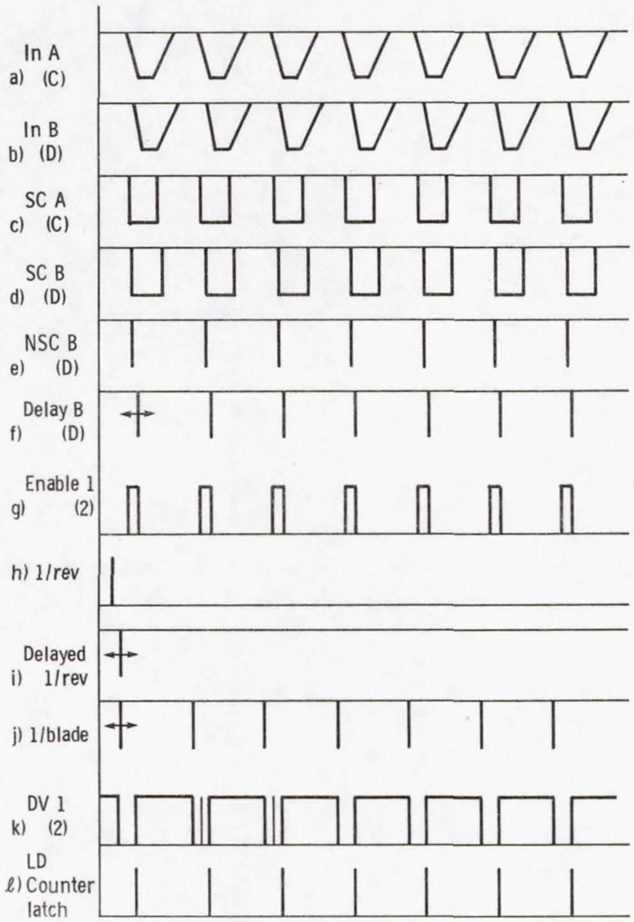

Figure 4. - Optical torquemeter timing diagram.

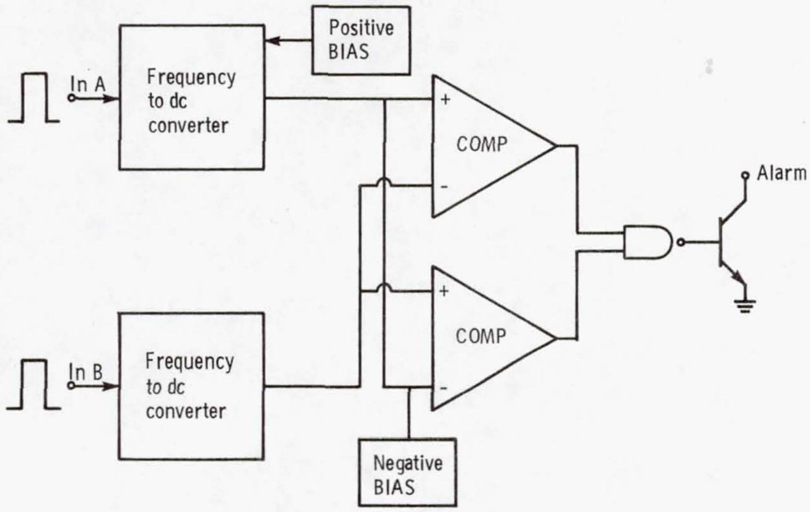

Figure 5. - Optical torquemeter probe failure detector block diagram.

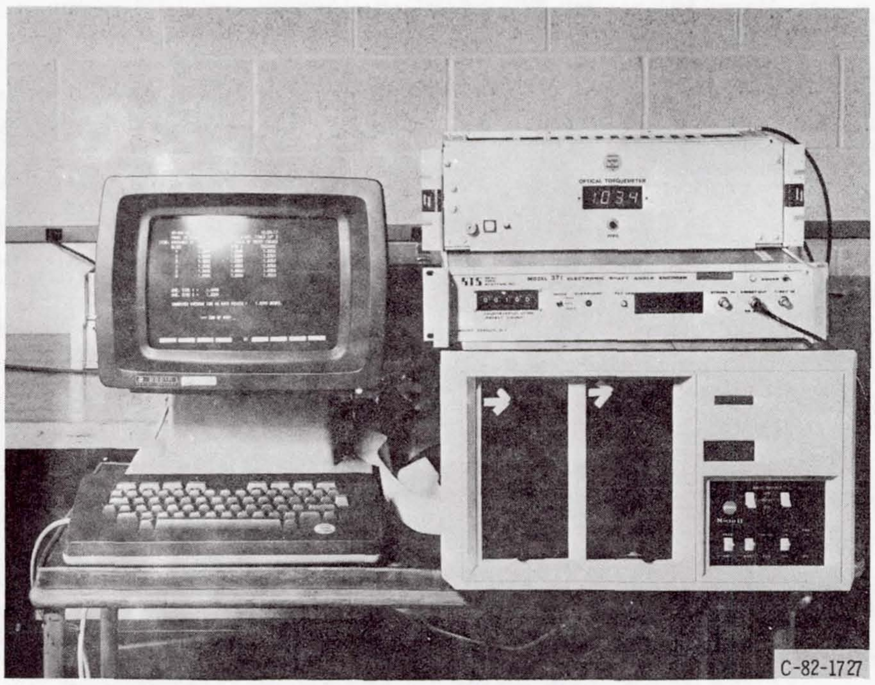

Figure 6. - Optical torquemeter electronics.

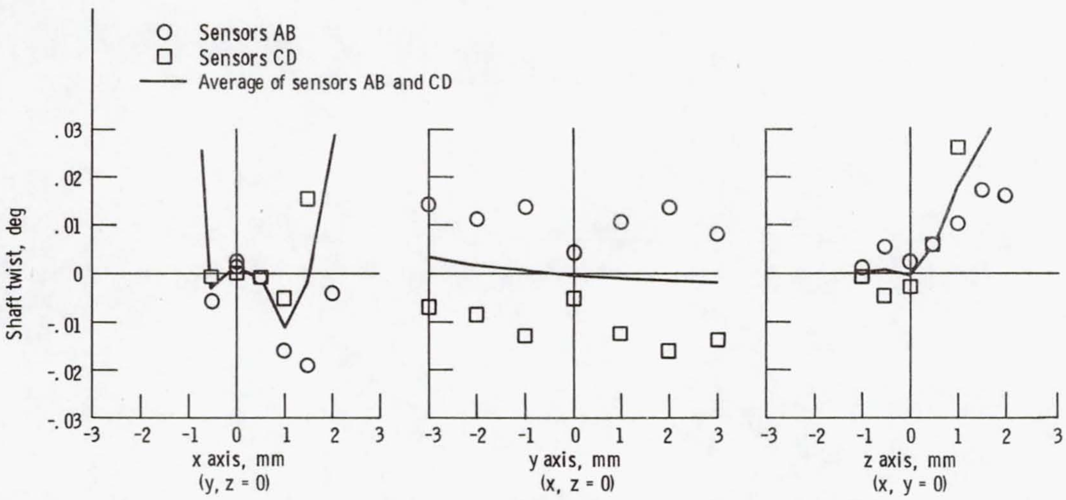

Figure 7. - Error of shaft twist at zero torque for translation along x, y, z axes.

PANEL METER OUTPUT IS IN UNITS OF DEGREES TIMES 10^3

AVERAGES OF 2 READINGS/BLADE OF ANGLE OF TWIST (deg)

BLADE	SIDE 1	SIDE 2	AVERAGE
1	0.0000	0.0000	0.0000
2	.0000	.0086	.0043
3	.0000	.0133	.0067
4	.0000	.0000	.0000
5	.0000	.0000	.0000
6	.0043	-.0021	.0011

AVERAGE SIDE 1 = 0.0007

AVERAGE SIDE 2 = 0.0033

COMBINED AVERAGE FOR 24 DATA POINTS = 0.0020 deg

(a)

PANEL METER OUTPUT IS IN UNITS OF DEGREES TIMES 10^3

AVERAGES OF 2 READINGS/BLADE OF ANGLE OF TWIST (deg)

BLADE	SIDE 1	SIDE 2	AVERAGE
1	0.0300	0.0300	0.0300
2	.0300	.0386	.0343
3	.0300	.0433	.0367
4	.0300	.0300	.0300
5	.0300	.0300	.0300
6	.0343	.0279	.0311

AVERAGE SIDE 1 = 0.0307

AVERAGE SIDE 2 = 0.0333

COMBINED AVERAGE FOR 24 DATA POINTS = 0.0320 deg

(b)

Figure 8. - System output in degrees of twist for simulated inputs. (a) Zero reading. (b) Electronic delay of 1 count at 30 000 rpm.

PANEL METER OUTPUT IS IN UNITS OF COUNTS TIMES 10 AVERAGES OF 4 READINGS/BLADE OF DATA COUNTS (FS = 255)

BLADE	SIDE 1	SIDE 2	AVERAGE
1	-6.8000	5.1000	-0.8500
2	-5.3000	3.1000	-1.1000
3	-1.9500	.7500	-.6000
4	3.4500	-3.8500	-.2000
5	1.5500	-2.0000	-.2250
6	-2.5000	1.9000	-.3000

AVERAGE SIDE 1 = -1.9250

AVERAGE SIDE 2 = 0.8333

COMBINED AVERAGE FOR 48 DATA POINTS = -0.5458 COUNTS

Figure 9. - Torquemeter zero stability data at 20 000 rpm in counts, for 12 000 counts per revolution.

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15. Supplementary Notes

16. Abstract

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