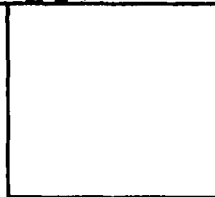


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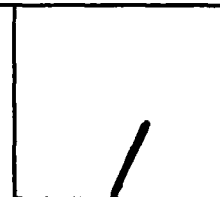
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TIP CLEARANCE SIGNAL PROCESSOR DEVELOPMENT

Lawrence W. Langley

Vatell Corporation
P.O. Box 66
Christiansburg, VA 24073

October 1988

Final Report for Period July 1987 - May 1988



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A signal processing system was designed and constructed to detect peaks of the Vatell eddy current clearance sensor signal, measure their amplitude and timing, and compute a correction for machine speed to indicate clearance and time of arrival for individual blades of a turbomachine. The system is based on an ADIIBM301 plug-in for the PC/XT, and consists of a second plug-in, along with software for signal detection and processing. Tests on a Pratt & Whitney JT15D first stage fan demonstrated timing precision of 0.16 micro-seconds and indicated individual blade clearances. The test results enable a projection of the capability to perform the speed correction calculation and indicate blade clearance continuously in real time.					
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TABLE OF CONTENTS

SUBJECT	PAGE
Background Information	1
Technical Objectives	7
Preliminary Design	9
Detailed Design	12
System Tests	19
Analysis of the Data	27
Conclusions	33
Future Research	33
References	35
Appendix A	36
Technical Data Certification	51
Abstract	51

BACKGROUND INFORMATION

During the spring of 1986 Vatel Corporation developed a new concept for casing-based measurements of tip clearance, and obtained industrial sponsorship for some tests of this concept in a NASA-owned Pratt & Whitney JT15D engine, located at the Virginia Polytechnic Institute (VPI) Turbomachinery Laboratory in Blacksburg, Virginia. The tests showed that a clearance probe based on the new concept was feasible, and would produce high quality signals indicating both tip clearance and blade time-of-arrival. The tests also indicated that an important capability for jet engine monitoring and control could be developed around the Vatel sensor.

The signals produced by the sensor indicate clearance distance by amplitude, but signal amplitude is also a function of speed. However, the relationship between speed and amplitude is precise enough to allow direct compensation for speed using blade timing measurements as a source of speed information.

Figure 1 is a schematic view of the Vatel sensor which illustrates its principles of operation. The sensor contains two magnets, a flux bridge and a coil, all within a housing which may be filled with an encapsulant. The sensor is shown in typical orientation relative to a moving turbomachine blade made of electrically conductive material such as titanium.

One of the two magnets (1) is oriented with its North pole adjacent to a flux bridge. The second magnet (2) is oriented with its South pole adjacent to the flux bridge. The combination of the two magnets and the flux bridge produces a static magnetic field in the region traversed by the blade, adjacent to and between the South pole of magnet (1) and the North pole of magnet (2). The shape of this field and its extent are as described by Herbert C. Roters in Chapter 5 of his textbook "Electromagnetic

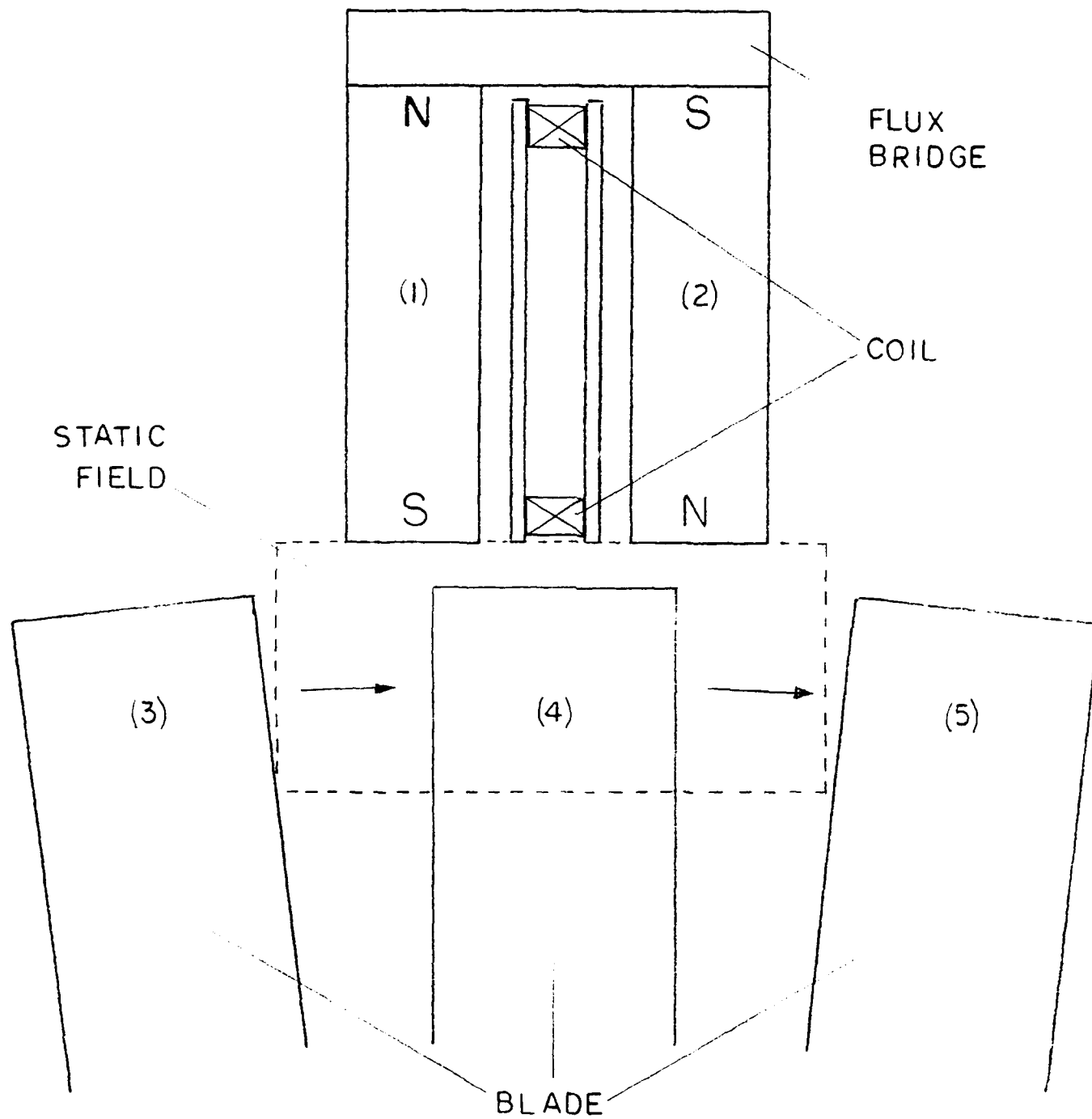


FIG. 1

Devices", published by Wiley. Figures 6a and 6b of the reference are particularly illustrative of the lines of force and the equipotential lines of the field of such a magnet. In the absence of any moving conductive objects in the region between the open poles of the two magnets, the field will not vary with time. Thus the field surrounding the coil will be constant, and no voltage will be produced at the terminals of the sensor. The effect of the blade on the static magnetic field, and the voltage produced by its motion in the coil, are best understood by visualizing that the blade is initially in a position (3) moving toward and through the position (4) to the position (5). As the blade begins to intercept field lines of the magnet, eddy currents will be induced in the conductive material of the blade. These currents will flow in the blade in a pattern and direction which oppose the increase in flux density passing through the blade material. The currents will effectively induce a magnetic field within the blade which is equal and opposite to that of the permanent magnet. External to the blade this field is effectively attached to the blade, and its motion relative to the coil will induce a voltage in the turns of the coil. This voltage is initially negative with the coil intercepting an increasing proportion of the eddy-current field. When the blade reaches the centered position (4) the eddy currents in the blade quickly reverse direction, because the field of the permanent magnet intercepted by the blade stops increasing and starts to decrease. The rapid reversal of eddy currents causes a rapid reversal of the induced field polarity seen by the coil, and a large positive peak voltage is produced because the field produced by these currents is closely coupled to the coil at this position. As the blade moves away from the centered position, the field intercepted by the nearest turns of the coil then decreases, and a second negative voltage peak is produced. It is negative because the polarity of the eddy currents has reversed and the blade is now moving away. The characteristic shape of the signal, shown in Figure 2 with polarity reversed, is the

BLADE Ø

23.5 μ s
9.48 mV

-29.5 μ s
5.65 mV

-3.0 μ s
-16.5 mV

Figure 2

result of the growth and decay of eddy currents in the blade and the progression of changes in their orientation with respect to the coil.

Eddy currents in the moving blade are produced by the motion of the blade through the permanent magnet field, and the amplitude of the field they produce is proportional to the velocity of the blade. The voltages induced in the coil by these fields are also produced by relative motion, and are proportional to the blade velocity as well. The combination of these two proportionalities yields a square-law relationship between the signal level and the speed of the blade. The shape of the signal does not change with speed because the resistivity of the blade material is low and the eddy currents are dissipated only slightly by resistive losses. The inductance of the coil has a minimal effect because currents are induced in it by changes in the external field, rather than by voltages imposed on its terminals. The signal is therefore an almost perfect indicator of mechanical position. Its frequency content is much higher than the decay time constant of the driving eddy currents and much lower than the detection circuit's time constants.

Coupling of the permanent magnetic field to the blade, and the coupling of the coil to eddy-current induced transient fields, are both affected by the angle between the blade chord and the axis of the coil. For maximum signal, the plane of the sensor, which is the same as the plane of the coil, should be parallel to the blade chord. This orientation yields a maximum coupling between the permanent magnet and the blade material, and a maximum coupling between the coil and the eddy currents in the blade.

Coupling between the magnetic field and coil of the sensor and the blade material is also affected by the distance from blade to sensor. As the gap between them is increased, the signal induced

by eddy currents will diminish. Thus the signal amplitude may be used for the measurement of blade clearance, if the effects of blade velocity can be compensated for.

Vatell submitted a 1987 SBIR proposal for development of 200°C rated sensor prototypes and for precise measurement of their characteristics in an actual jet engine compressor environment. The Air Force funded this work as contract F33615-87-C-2801. Measurements made during this contract showed the relationship between speed, clearance and signal amplitude to be expressed accurately by the equation:

$$\text{Amplitude(mv.)} = \frac{AS^2 - BS + C}{Y + D}$$

Where

S = Speed - RPM
Y = Clearance - Inches

The values of constants A, B, C and D for two sensors tested during this contract were:

Constant	Sensor #1	Sensor #4
A	1.03 X 10 ⁻⁸	9.67 X 10 ⁻⁹
B	4.89 X 10 ⁻⁵	6.18 X 10 ⁻⁵
C	0.075	0.159
D	0.0245	0.0220

To compensate a sensor for speed variation, the equation is solved for Y, thus:

$$\text{Clearance(in.)} = \frac{AS^2 - BS + C}{\text{Amplitude(mv.)}} - D$$

Using constants A, B, C and D for the sensor employed.

To make this sensor generally useful in tip clearance

measurements, some means of carrying out the speed compensation, preferably on-line, is needed. Under the current contract Vatell has developed such a means, in the form of a breadboard signal processing module.

TECHNICAL OBJECTIVES

The principal objective of this contract was to design and build a breadboard signal processing module for use with the clearance sensors being developed under contract F33615-87-C-2801.

Functions to be performed by the module, as listed in the 1987 SBIR Vatell proposal, were:

- (1) Precise, wide-band differential amplification
- (2) Conversion of signal amplitude to digital values
- (3) Threshold detection
- (4) Peak detection
- (5) Timing of signal peaks
- (6) Computation of machine speed
- (7) Computation of clearance
- (8) Communications with a host processor

Figure 3 is a block diagram of the processor from the Vatell proposal. The tentative organization for the module circuits was described as follows; signals from the sensor 9 would be amplified by a low-noise differential amplifier 5, for example a Dynamics Model 7525, to single-ended amplitude sufficient for high precision analog-to-digital conversion. This function would be performed by an A-D convertor 6, for example an Analogic ADAM 826-1 16-bit convertor with integral sample and hold, capable of converting the output of amplifier 5 to a 16 bit number in 2.3 microseconds. Conversion results would be read by the microprocessor 2, which also reads values of time from a clock 4. The software algorithm to be used for computation of clearance,

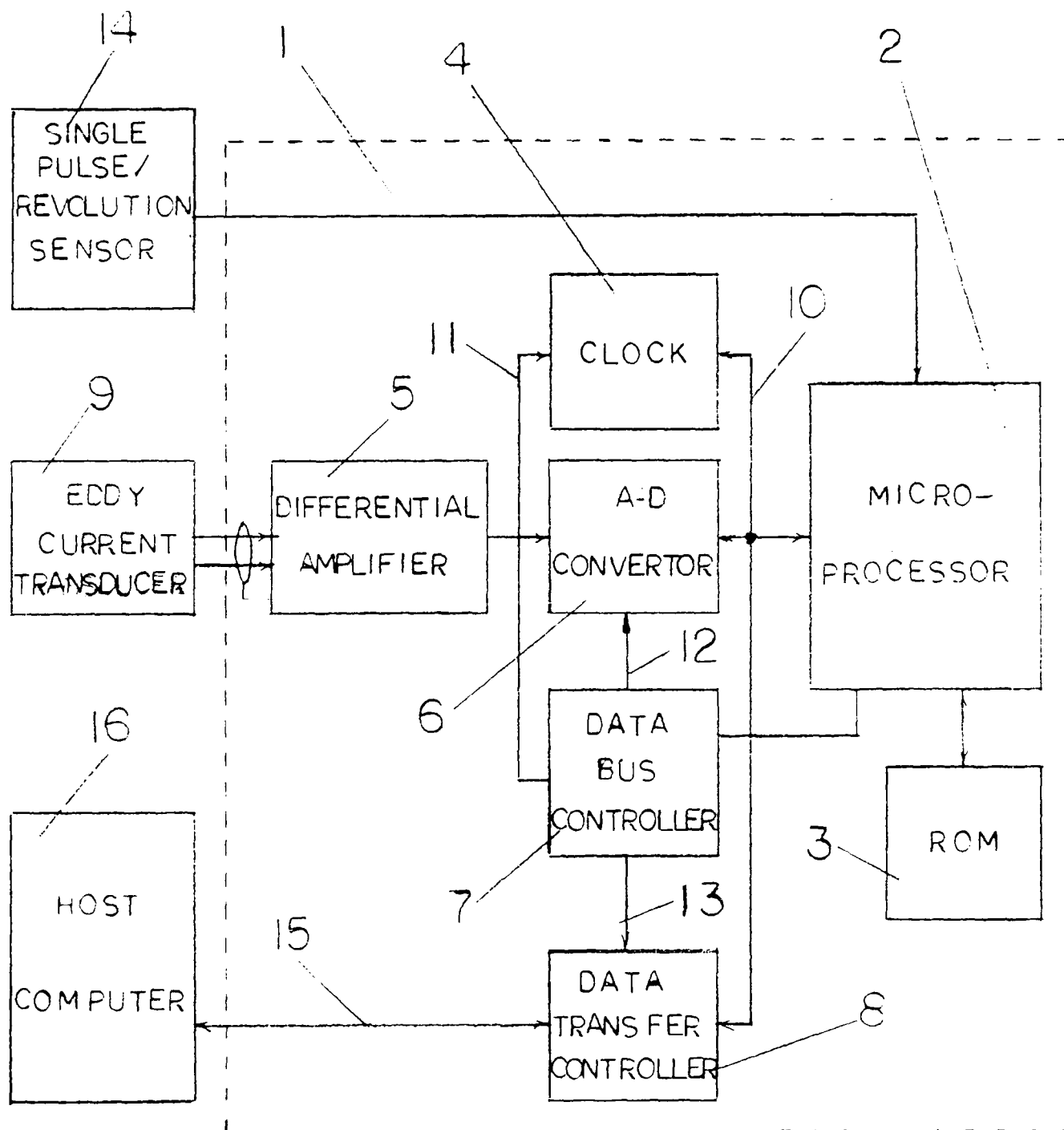


Figure 3

and the coefficients initially employed, were to be based on experimental test results for the clearance sensors being developed under the parallel sensor development contract. The coefficients (and, if necessary, the algorithm itself) would be modified as required. The end point of the computations would be:

- (1) a clearance value for the blade which has just passed the sensor;
- (2) a time value for the signal peak from this blade;
- (3) the value for machine speed used in computing clearance; and
- (4) the current blade number.

These values would all be computed in the time period between blade signal peaks and transferred during this period to a host computer. The host computer would store computed blade values for the current revolution, and compute whatever statistics of clearance, timing or other values are desired. Determination of these host computer functions, and their programming, were not to be included in this project.

Operation of the processor would be verified using signals from a sensor on the first stage fan of the JT15D at the VPI airport. This fan is 21 inches in diameter, has 28 blades, and operates at a maximum speed of approximately 16,000 rpm. A once-per-revolution sensor had been fitted to this engine as part of the work on the sensor contract.

PRELIMINARY DESIGN

A tentative selection of the Texas Instruments TMS 32010 Digital Signal Processor chip had been made at the time of the proposal. This chip was not the fastest or most powerful available, but was the only one being widely used by board-level sub-system

suppliers. One of these suppliers, Atlanta Signal Processing Incorporated, offered a signal processing plug-in board for the IBM PC/XT based on this chip. This plug-in, the ADPIBM301, was designed to perform some of the functions required for this contract. Atlanta Signal Processing also offered design and debugging tools for TMS32010 program development. The ADPIBM301 was selected as the base for the Vatel signal processing module.

During the initial design calculations, it was determined that peak timing resolution would be severely limited if the original concept of software peak detection was used. That concept required that the analog sensor signal waveform be converted at the highest possible rate to a sequence of digital values. Each value would then be compared to the preceding one by software, in a subtract (or compare) and branch loop. The time for the minimum number of instructions to do this, added to an A/D conversion time, would yield a time precision of no better than 3 microseconds. Because one of the proposed applications for the signal processing module would be to measure blade time of passage for vibration and twist sensing, it was decided that this precision would not be acceptable. Instead, a hardware peak sensing scheme was devised and substituted for the software approach. This change had some side benefits: the A/D conversion cycle timing requirement could be relaxed, and a sample and hold circuit could be used to improve the precision of sample timing even further.

In the 1987 SBIR proposal Work Plan it was pointed out that because of the short duration and limited funding of the project the signal processing module would have to be developed using some commercially available parts. One of the parts originally selected was the Dynamics Model 7525 differential amplifier: it was proposed to amplify the balanced sensor signal to an A/D conversion voltage level. This amplifier is only available in a packaged unit designed for its own special housing; the total

outline dimensions of the housing are greater than those of the PC/XT. Early tests of the new sensor indicated that its voltage output would be at least ten times greater than that of the original sensor. With this new sensor signal a very low noise, high gain amplifier would not be required. It was decided to substitute an IC differential amplifier on the module board for the Model 7525.

As a result of these decisions; i.e. to employ the Atlanta Signal Processor ADPIBM310 board, to use an on-board IC differential amplifier instead of the Dynamics unit, and to substitute a hardware peak finding and sampling method for the software method, it became possible to fit all the required signal processing functions into a single processor board. The decision to make this board a PC/XT plug-in was a natural result. The configuration finally adopted was;

- (1) a Victor PC2 microcomputer with video monitor;
- (2) a slightly modified ADPIBM310 board in one host computer slot, containing the TMS 32010 signal processing chip, A/D converter and memory; and
- (3) a Vattell-designed signal acquisition board in the adjacent slot, containing differential amplifier, peak detection, timing and control circuits.

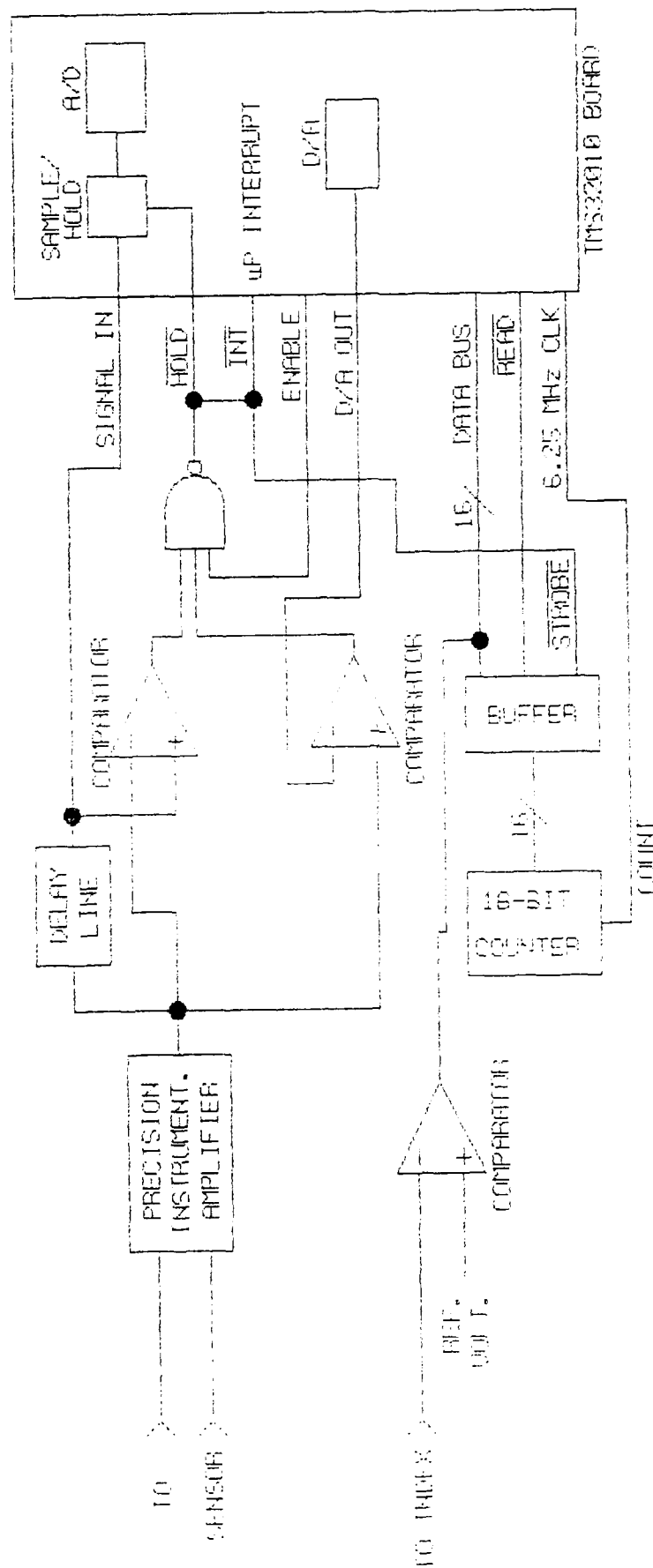
The two boards would be cross-connected by a ribbon cable, which would allow rapid and controlled data transfer between them. With this configuration it was not necessary to design a communications link between the PC and the module; software could be written for the PC to directly access module memory on the PC bus, and the Atlanta Signal Processing debugger could be used to control and test the system in operation. The detailed system and circuit designs were carried out on this basis.

DETAILED DESIGN

Figure 4 is a block diagram of the circuits on the signal acquisition board. The sensor signal is amplified to a proper level (0-5 volts dc) for analog-to-digital conversion, by a precision differential input amplifier. The output of the precision amplifier drives the two inputs of a signal comparator, one directly and the other through a 0.5 microsecond delay line. With this arrangement, every time the sensor signal reaches a peak (positive or negative) the output of the signal comparator reverses. The reversal of signal comparator output from positive to negative indicates that a positive peak has occurred in the sensor signal. To prevent this circuit from triggering analog to digital conversions on other peaks of the waveform or on noise, the signal comparator output is gated by another comparator. This second comparator compares the signal to a threshold (D/A) voltage, and only allows triggering of A/D conversion on a peak above the threshold. The threshold is set by software and can be adjusted dynamically for the best compromise between peak detector dynamic range and noise immunity.

When a positive peak in the sensor signal is detected, the analog voltage value of the delayed signal is captured by the ADPBM310 sample and hold circuit, which has an aperture delay and uncertainty of less than 0.1µsec. At the same time the number in a continuously running 18-bit timing counter is transferred to a buffer. This number is the peak occurrence time; with a counting rate of 6.25 mhz it has a precision of 0.16 µsec. The A/D conversion cycle by the ADPBM310 is also commanded at this time. The ADPBM310 board then increments the blade counter and performs its calculations.

Figure 4 also shows that the module receives the once-per-revolution (index) signal. This signal is derived from a photoelectric detector which scans a retroreflective paint strip



5/88
44K

SYSTEM BLOCK DIAGRAM

Figure 4

on the engine spinner. The once-per-revolution signal is used to indicate the space between Blades 28 and 1; the signal itself is not used directly in blade timing. When the blade number is incremented by the ADPIBM310, the once-per-revolution signal is checked to determine if it has made a negative-going transition since the last blade count. If so, the blade count is reset to 1. The blade timing is indicated as 0, but the continuously running counter is not reset. The next and all succeeding values for blade timing are obtained by subtracting the old timer value from the new, then adding the difference to the count for the preceding blade. Thus all blade timing information is referenced to blade 1, but not to the once-per-revolution index. This is done because the timing of the once-per-revolution index may vary with engine speed, even though it always occurs between blades 28 and 1. Figure 5 is an oscillogram of the once-per-revolution signal. A photograph of the completed Vatel1 signal acquisition module is given as Figure 6. Figure 7 shows both boards installed in the Victor PC2.

The ADPIBM310 board is designed for processing of continuous waveforms such as audio signals, using FFT or digital filtering algorithms. Its analog to digital convertor is controlled to sample the signal waveform at regular intervals, with software selection of the sampling rate. The processing of signals from the Vatel1 sensor requires a different mode of control. Analog to digital conversion must be triggered at a precise time relative to the waveform, under control of the peak sensing circuit. To achieve this it was necessary to modify the A/D control circuits. Figure 8 is a photograph of the ADPIBM310 board which shows this modification.

One of the most important selection criteria for the Texas Instruments TMS 32010 Digital Signal Processor chip, and the ADPIBM310 board, was that the 32010 chip instruction set included a divide primitive instruction which could be used to build a

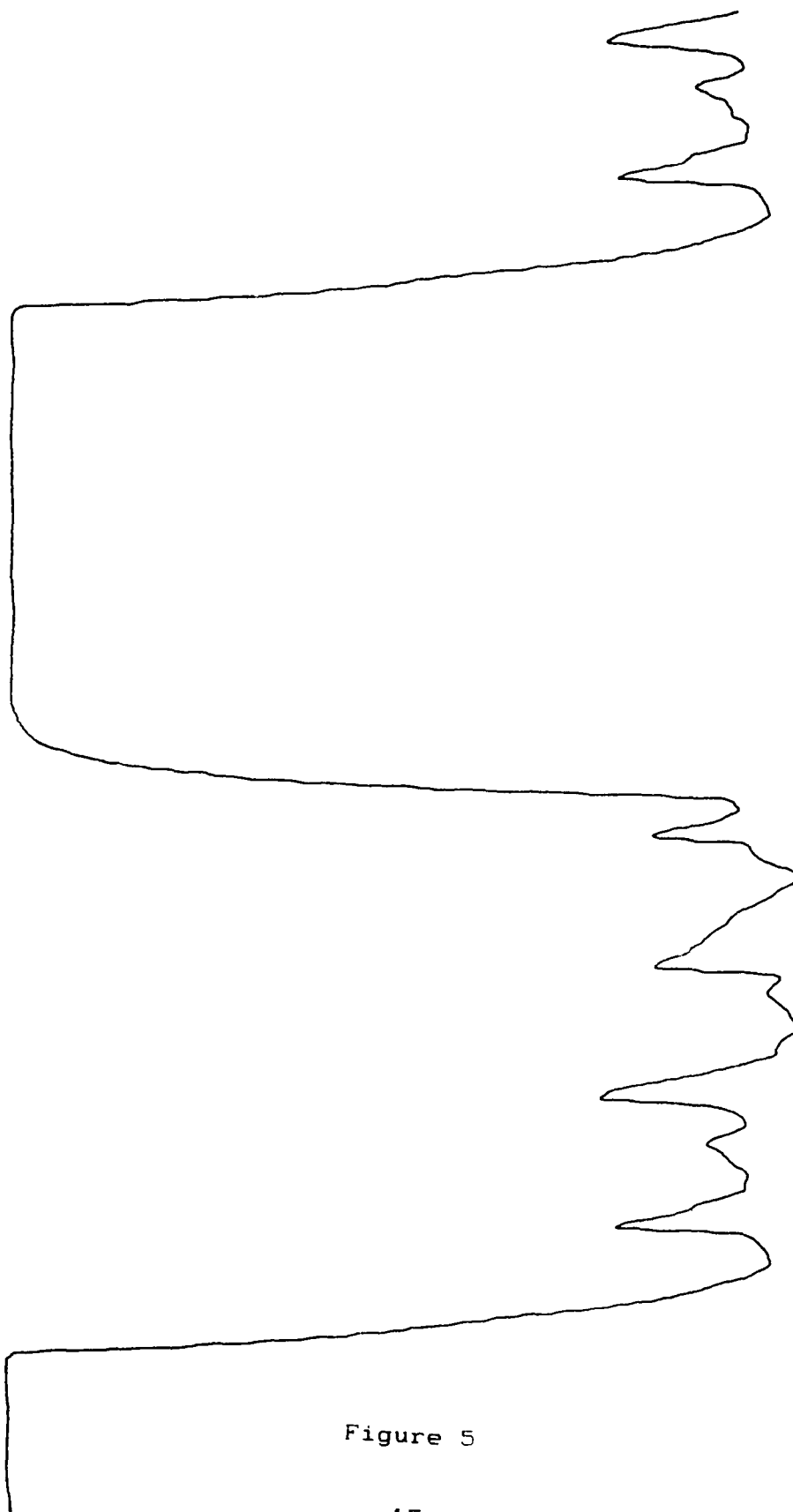


Figure 5

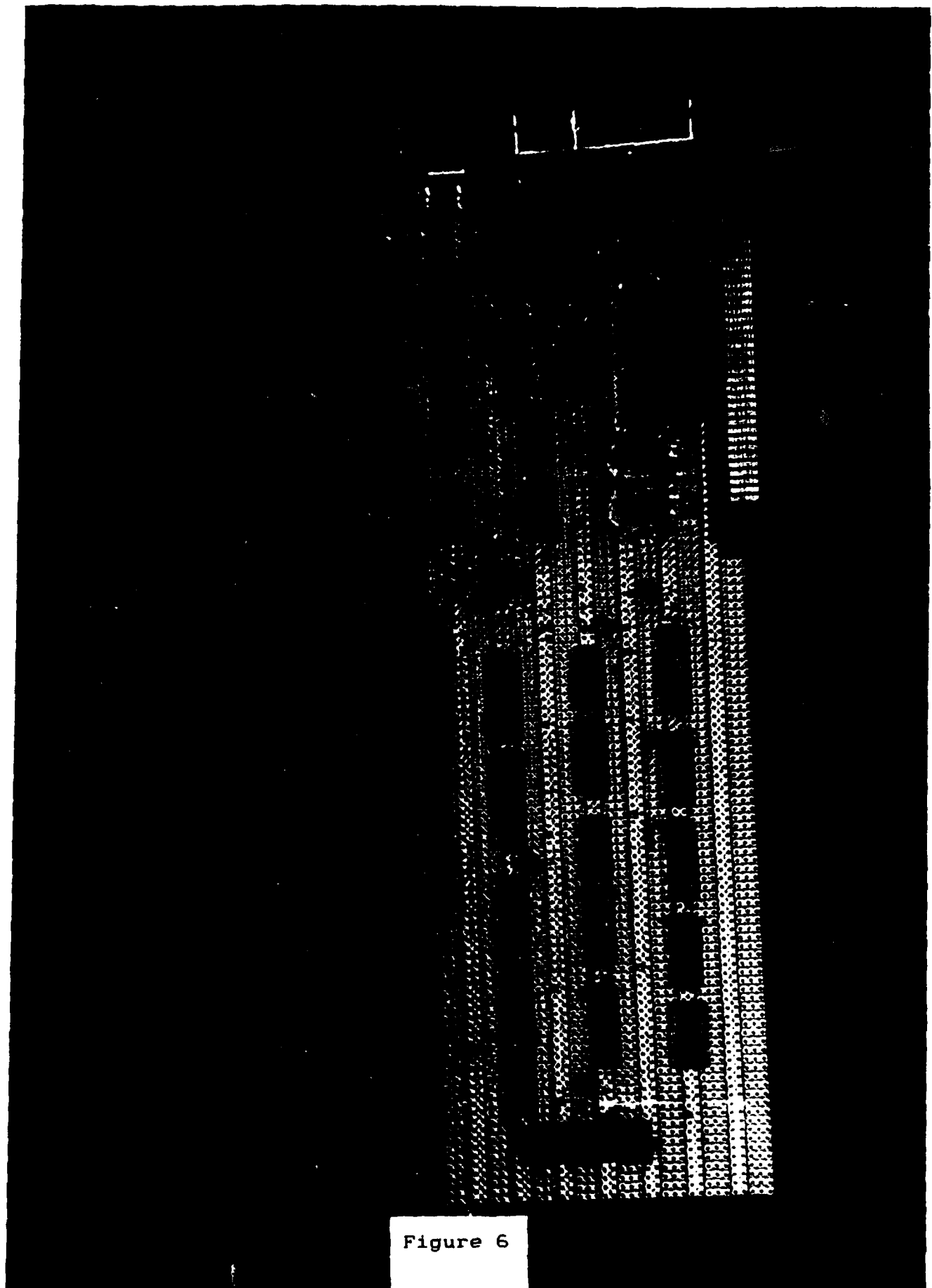


Figure 6

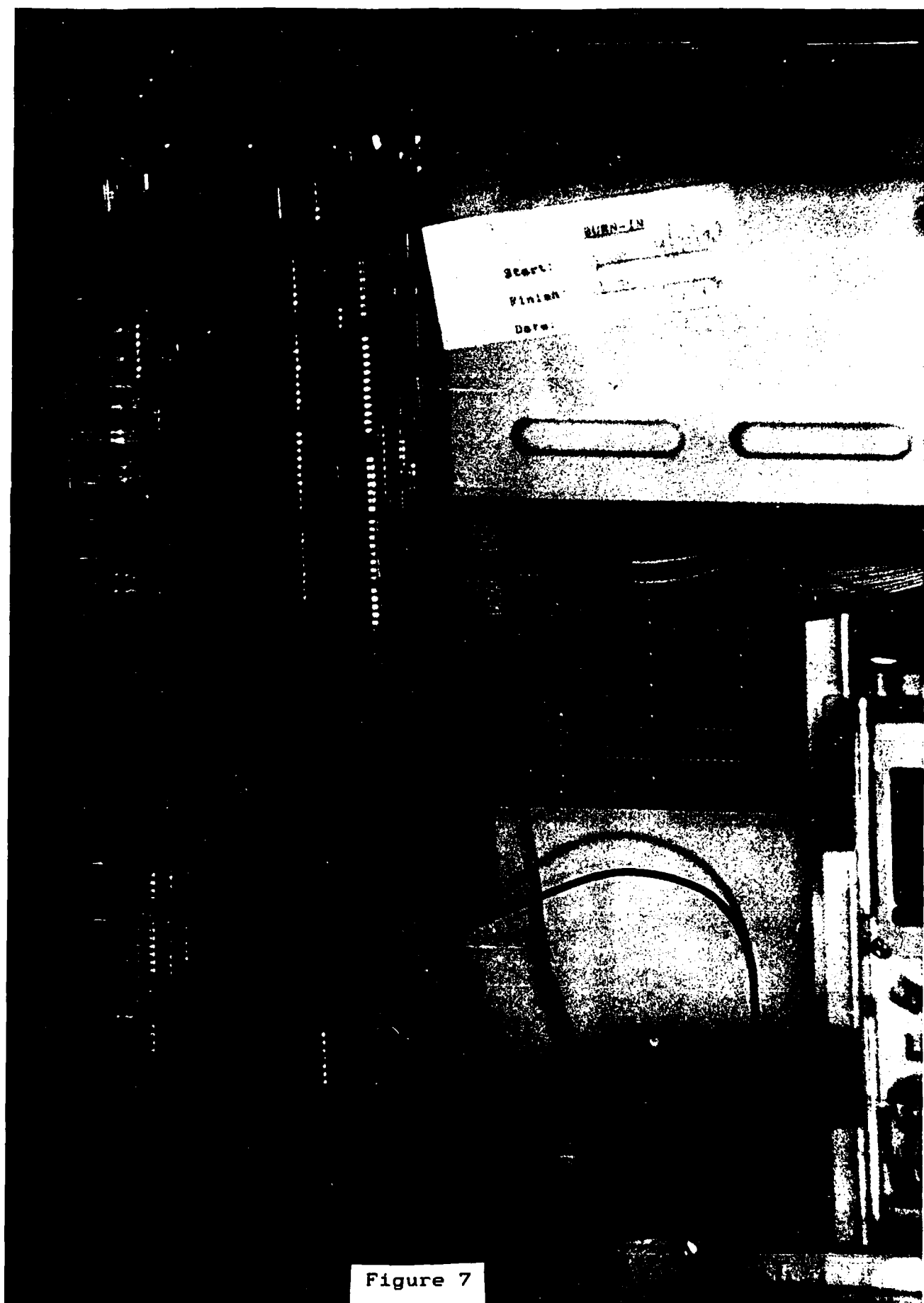


Figure 7

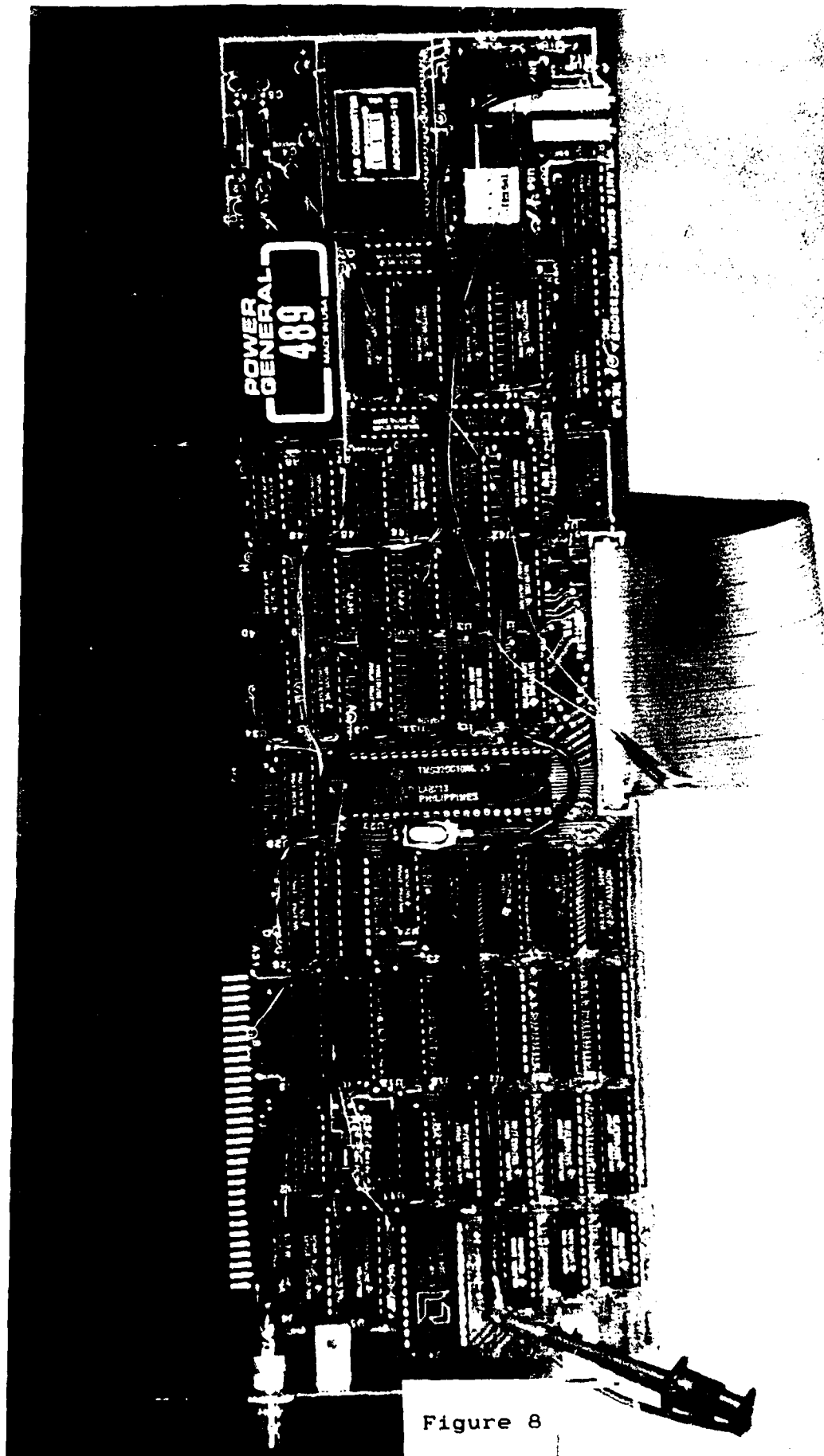


Figure 8

double precision divide macro. VatelI was led to believe that this would be a straightforward process, and actual writing of the macro was left to a late stage in the programming. The macro writing task was found to be a great deal more difficult than originally anticipated. VatelI contacted the supplier for help, and was told that no one had ever written a double precision divide for this chip. It would, indeed, be a very difficult task, and TI would not even quote on doing it. Furthermore, the TMS 32010 chip was "no longer supported" for program development, having been replaced by more advanced, faster hardware.

The only possible recourse to an expensive, time consuming replacement of the TMS 32010 was to perform the speed compensation calculations in the host computer. The amplitude and timing of peaks for a full revolution would be read by the host computer, which would then calculate clearances for all 28 peaks, using a Basic routine. Of course this could not be done in real time. Software for the TMS 32010 and the PC were completed according to this modified plan. Appendix A is a listing of the final TMS 32010 signal acquisition software and the host Basic routine for speed compensation.

SYSTEM TESTS

After bench tests of the signal acquisition board, the ADPIBM310 board and the host computer, the system was assembled and installed in the JT15D test stand at VPI and connected to the clearance and once-per-revolution sensors. The experimental installation is shown in Figure 9. The PC is at the far end of the engine control panel, together with the once-per-revolution sensor power supply and load circuits, which are housed in an aluminum box on the shelf. Figure 10 shows the engine mounted on its test stand, and Figure 11 shows the once-per-revolution sensor mounted adjacent to the first stage fan on the engine housing.

A number of minor problems were encountered during the tests. Hysteresis of the comparator used for peak detection was too great, and had to be reduced. Several software errors were found and corrected. The noise level on the amplified sensor signal was found to be excessive. While the signal entering the board was extremely clean, the high frequency background noise caused by operation of digital circuits on the ADPIBM310 and the signal acquisition board was almost 50 millivolts peak-to-peak at the output of the final stage of amplification, more than 1% of the peak signal. After a thorough review of the signal acquisition board layout and circuits, the following modifications were made:

- (1) power supply lines on the board were divided into analog and digital groups, with separate connections back to the power source on the board;
- (2) an RC bypass network was added to each leg of the first stage amplifier IC supply; and
- (3) the bandwidth of the second stage of amplification was limited to 300 khz by addition of a filter network.

While these measures reduced noise by 1-2 db., it was still felt to be excessive. Reducing noise to an acceptable level (less than 5 mv.) would necessitate a completely new layout on a multi-layer board with separate analog and digital ground planes, and would probably require complete electrostatic and magnetic shielding of the analog circuits. At this point in the project, VPI's schedule for use of the JT15D called for it to be removed from service for major modifications in a few days. It was decided to complete the module tests without any further noise reduction efforts, to try to prove its capabilities without a costly and time-consuming major re-design.

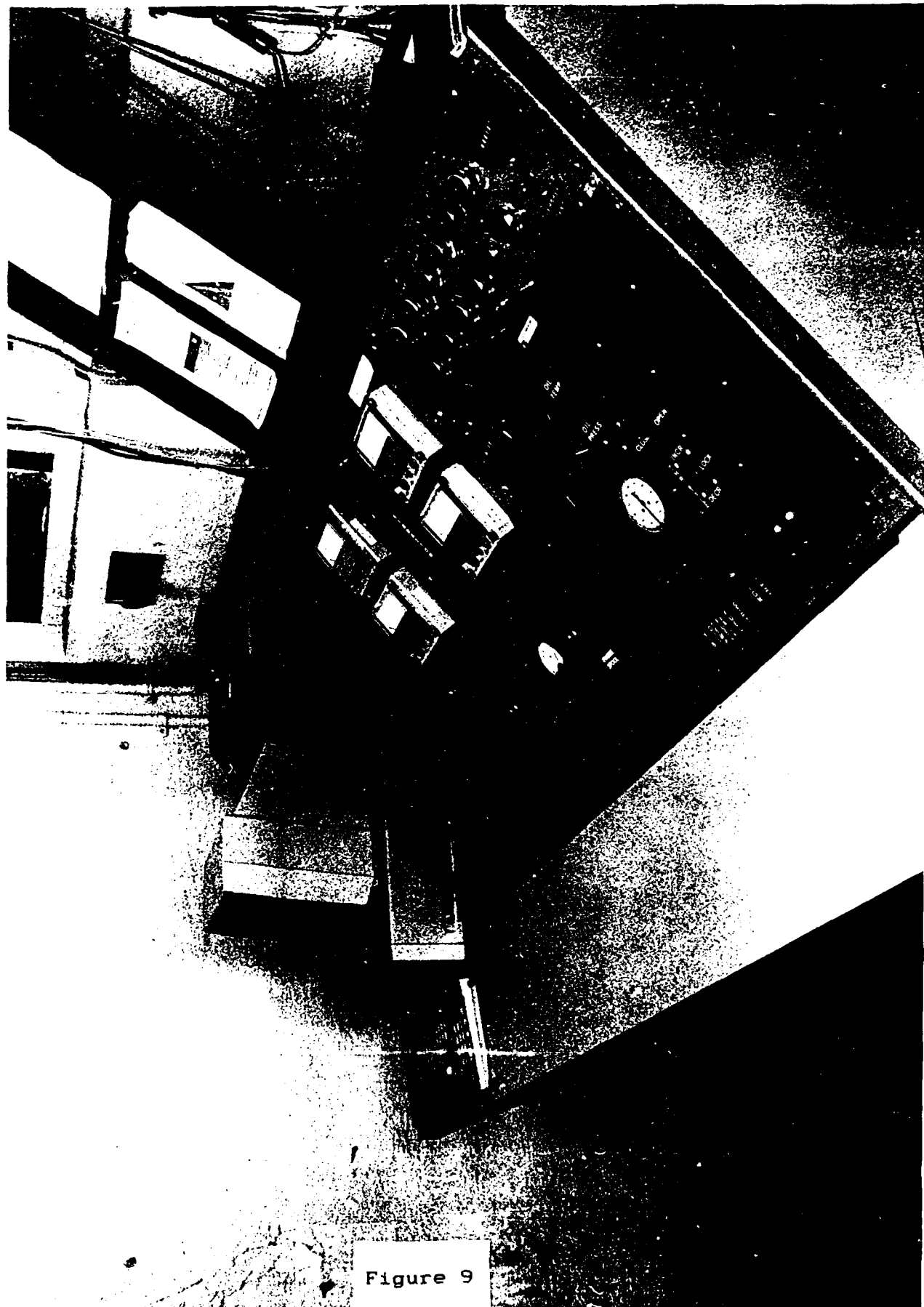


Figure 9

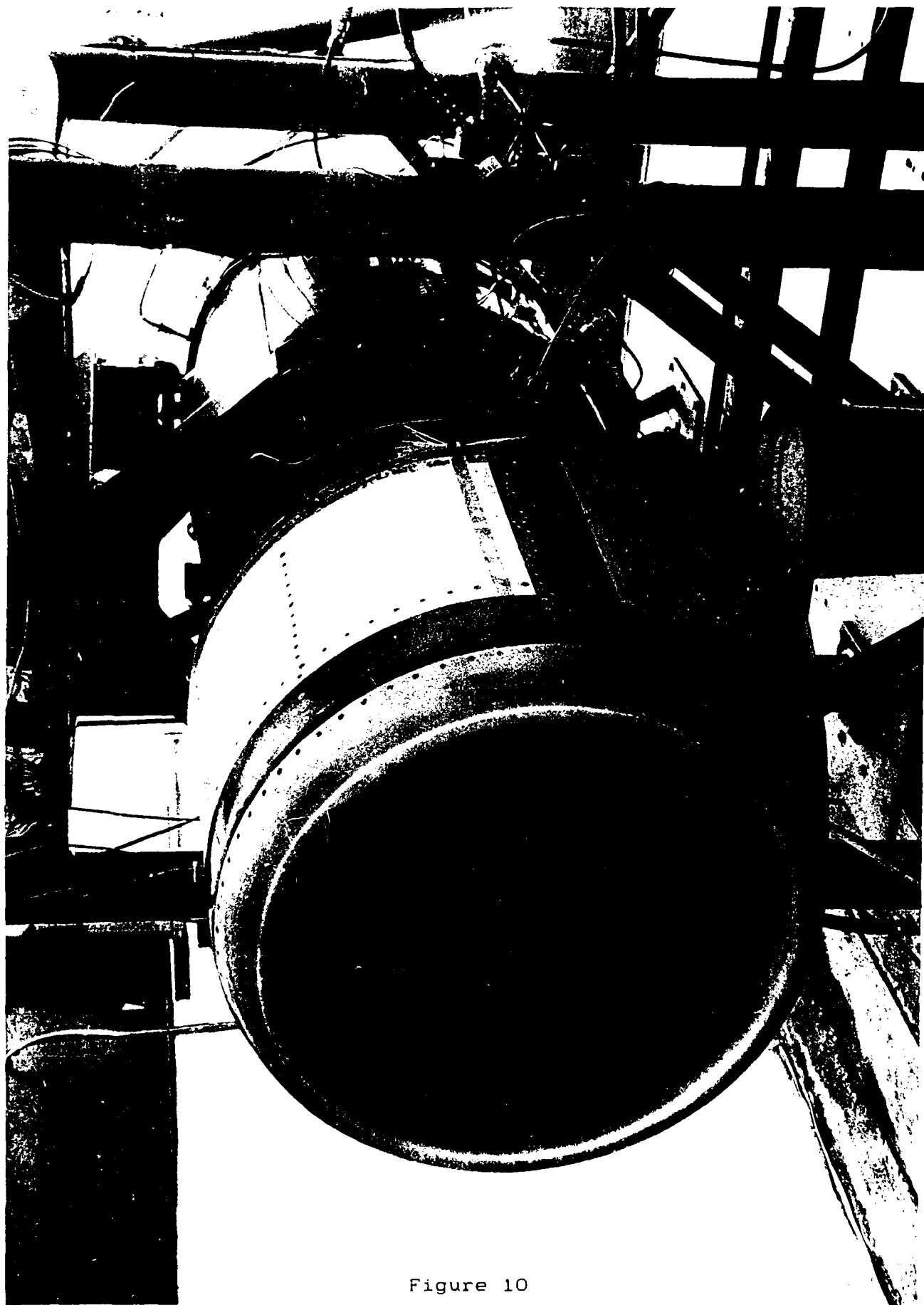


Figure 10

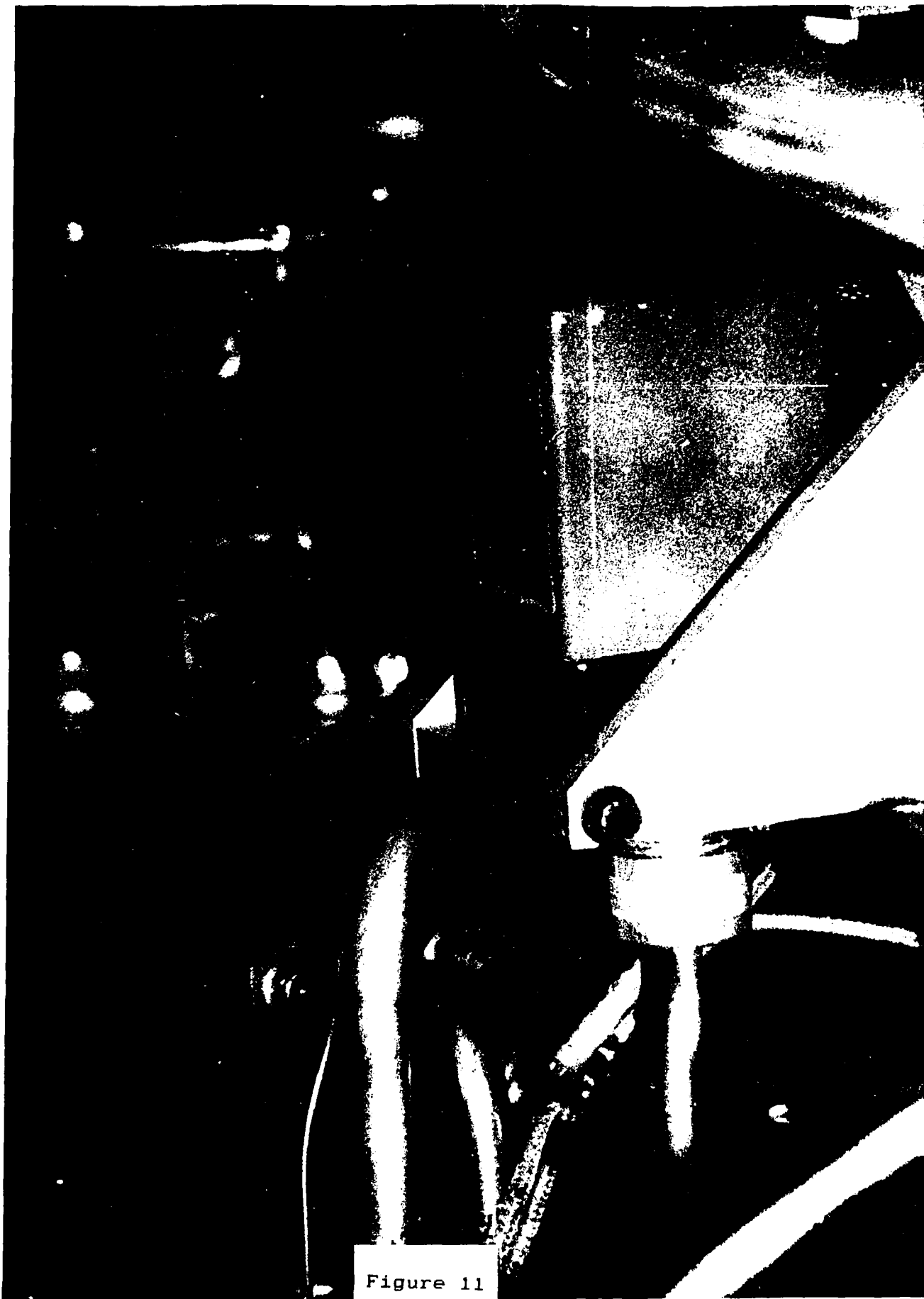


Figure 11

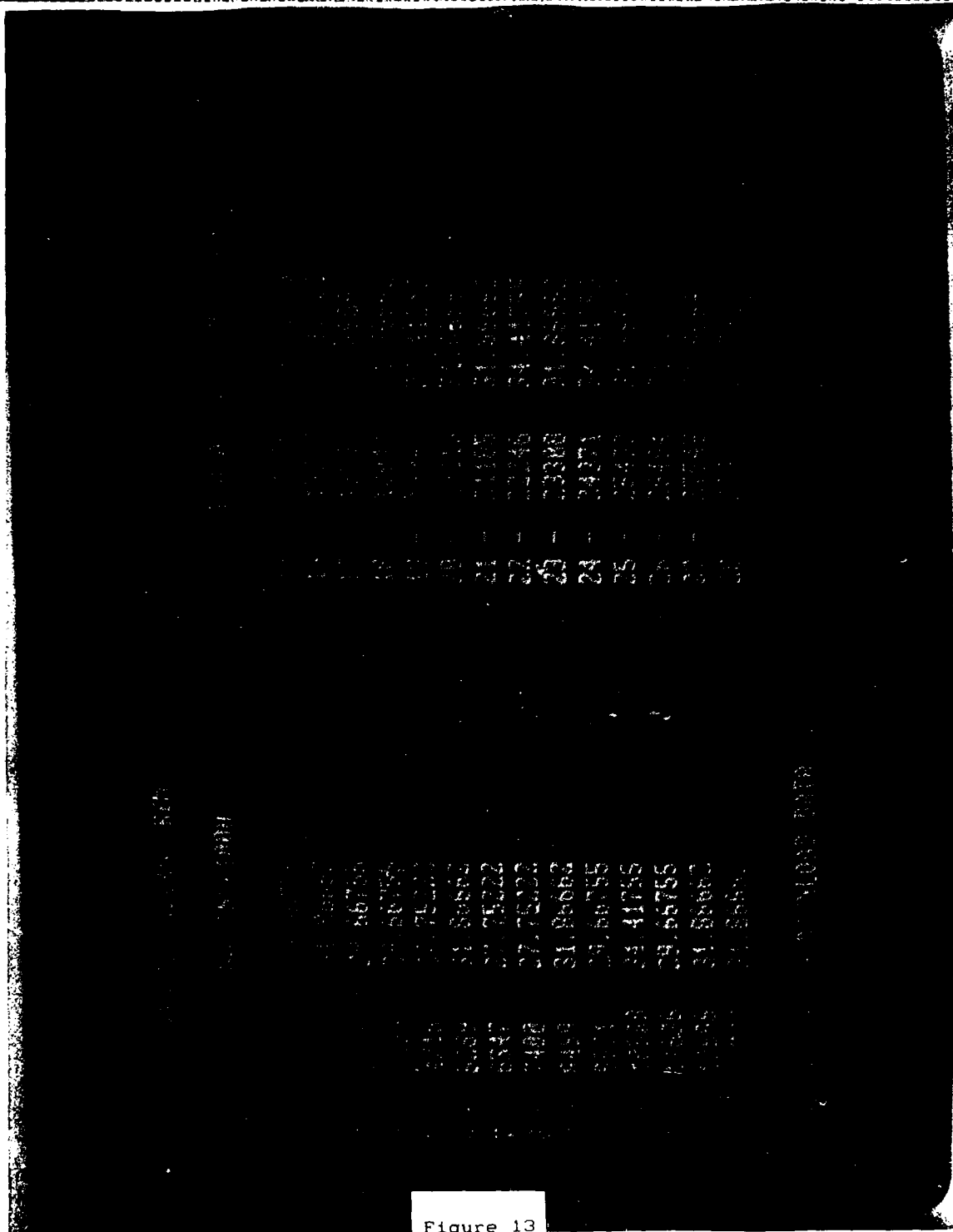


Figure 1

23. 46436	23. 46436
24. 97648	24. 97648
25. 46436	25. 46436
26. 44816	26. 44816
27. 19839	27. 19839
28. 46436	28. 46436
29. 99622	29. 99622
30. 46436	30. 46436
31. 46436	31. 46436
32. 46436	32. 46436
33. 99622	33. 99622

100% DOWNLOAD DATA...

Figure 14

Figures 12, 13 and 14 show the monitor displays resulting from the final module tests, at three different engine speeds. The calculated speed is displayed at the upper left of the screen. The time value for blade 1 is indicated as 0, and all other blade times are referenced to this value. The least count for blade timing is equal to 0.16 μ seconds. This is equivalent to a tangential displacement of approximately 0.002 inches at a speed of 15,000 rpm. Clearance values were calculated by the host computer using the following constants:

$$\begin{array}{ll} A = 1.2 \times 10^{-8} & B = -1 \times 10^{-4} \\ C = .31 & D = .02 \end{array}$$

In addition a scaling multiplier for amplitude, $K_1 = 7 \times 10^{-5}$, was used to adjust for sensor gain, amplifier gain and analog to digital conversion gain. The factors A, B, C and D used in these tests were different from those calculated for the sensor. Because time ran out on the engine test, there was no opportunity to correct these values.

While the clearance calculation was performed off-line, the results were the same as they would have been if the calculation had been done by the TMS32010 during the interval between blades. The TMS32010 program for acquiring data used 122 instructions, executing in approximately 30-32 microseconds. There is time for execution of approximately 400 instructions during the interval between blades at the highest speed. Thus the concept of calculating clearance in real time appears to be viable.

ANALYSIS OF THE DATA

Tables 1, 2 and 3 show the results of comparisons between the times of arrival actually recorded and "ideal" times, for the three speeds tested. "Ideal" times were calculated by dividing the Blade 28 arrival time by 27, and then multiplying by the

Analysis of Vatel Sensor Output - Signal Processor Data

Turbine Speed is 11,263.97 RPM

Blade Number	T-O-A	Ideal Time	Time Error	Delta Time
1	0			
2	1196	1189	7	1196
3	2368	2378	-10	1172
4	3571	3567	4	1203
5	4753	4756	-3	1182
6	5953	5945	8	1200
7	7133	7134	-1	1180
8	8330	8324	6	1197
9	9523	9513	10	1193
10	10717	10702	15	1194
11	11871	11891	-20	1154
12	13080	13080	0	1209
13	14256	14269	-13	1176
14	15475	15458	17	1219
15	16656	16647	9	1181
16	17845	17836	9	1189
17	19022	19025	-3	1177
18	20225	20214	11	1203
19	21386	21403	-17	1161
20	22573	22592	-19	1187
21	23777	23781	-4	1204
22	24981	24971	10	1204
23	26167	26160	7	1186
24	27351	27349	2	1184
25	28531	28538	-7	1180
26	29719	29727	-8	1188
27	30921	30916	5	1202
28	32105	32105	0	1184

Table 1

Analysis of Vatel Sensor Output - Signal Processor Data

Turbine Speed is 12,645 RPM

Blade Number	T-O-A	Ideal Time	Time Error	Delta Time
1	0			
2	1051	1059	-8	1051
3	2110	2118	-8	1059
4	3159	3178	-19	1049
5	4216	4237	-21	1057
6	5289	5296	-7	1073
7	6347	6355	-8	1058
8	7400	7415	-15	1053
9	8469	8474	-5	1069
10	9531	9533	-2	1062
11	10588	10592	-4	1057
12	11636	11651	-15	1048
13	12696	12711	-15	1060
14	13772	13770	2	1076
15	14836	14829	7	1064
16	15893	15888	5	1057
17	16946	16948	-2	1053
18	18011	18007	4	1065
19	19067	19066	1	1056
20	20116	20125	-9	1049
21	21185	21184	1	1069
22	22246	22244	2	1061
23	23308	23303	5	1062
24	24371	24362	9	1063
25	25433	25421	12	1062
26	26484	26481	3	1051
27	27545	27540	5	1061
28	28599	28599	0	1054

Table 2

Analysis of Vatell Sensor Output - Signal Processor Data

Turbine Speed is 14,454.77 RPM

Blade Number	T-O-A	Ideal Time	Time Error	Delta Time
1	0			
2	922	926	-4	922
3	1843	1853	-10	921
4	2771	2779	-8	928
5	3697	3705	-8	926
6	4622	4632	-10	925
7	5559	5558	1	937
8	6477	6485	-8	918
9	7410	7411	-1	933
10	8335	8337	-2	925
11	9263	9264	-1	928
12	10188	10190	-2	925
13	11113	11116	-3	925
14	12042	12043	-1	929
15	12974	12969	5	932
16	13890	13896	-6	916
17	14819	14822	-3	929
18	15753	15748	5	934
19	16671	16675	-4	918
20	17601	17601	0	930
21	18538	18527	11	937
22	19450	19454	-4	912
23	20385	20380	5	935
24	21313	21307	6	928
25	22233	22233	0	920
26	23161	23159	2	928
27	24084	24086	-2	923
	25012	25012	0	928

Table 3

blade number less one. The maximum difference between "ideal" time and measured time for each of the three speeds is 1.7%, 2.0% and 1.2% of the blade to blade interval. Arrival times are most accurate for the highest speed, as might be expected. The effect of a 10 times improvement in signal-to-noise ratio, easily feasible with proper amplifier design, should be to bring these within one count of the proper value. This would result in a timing precision of 0.16 microseconds, representing less than 0.002" tangential displacement of the blades.

The clearance numbers calculated and displayed on the monitor (Figures 12, 13 and 14) are in error for three known reasons. First, the large amount of noise on the signal interferes with peak detection. Because an A/D conversion cycle may be triggered ahead of the waveform peak, the voltage sampled and converted could be grossly wrong. A noise pulse at the peak would not change the timing, but would affect the amplitude measurement.

The second source of error is in the handling of analog to digital results by the TMS 32010 software. While the clearance numbers displayed on the screen show five significant figures, only a few different values are represented. By back-calculating convertor values from the results shown on the screen for 14,454.77 RPM, this error can be localized.

Indicated Clearance	Calculated A/D Value	Equivalent A/D 12 bits
33.08344	592	0010 0101 0000
31.38583	624	0010 0111 0000
29.85384	656	0010 1001 0000
28.46436	688	0010 1011 0000
27.19839	720	0010 1101 0000
26.04016	752	0010 1111 0000
24.97648	784	0011 0001 0000
23.99622	816	0011 0011 0000

From this analysis it can be seen that the 5 least significant

bits of convertor data are not changing. The reason for this is unknown. The analog to digital convertor was tested independently, and produced the full range of output numbers. The complementing and shifting routine for A/D data was also debugged and checked thoroughly. The cause of the problem may be noise affecting the sample and hold output.

The third source of error is the use of incorrect values for the constants in the clearance calculation. Values for the constants A, B, C and D were written into the program before measurements and analysis of the sensor actually used in the tests. These constants were not corrected in the program because time ran out for the experiment: a great deal more time was consumed in troubleshooting the system than anticipated, most of it with the engine running.

Clearances can be calculated using the known constants A, B, C and D for the sensor used in these tests, but the clearance for one blade must be known (or assumed) to determine the value for the constant K_s in the program. If it is assumed that the highest signal amplitude measured at 14,454.77 RPM represents a physical clearance of .025 inches, then $K_s = .03353$, and the A/D measurements for that speed would represent a range of clearances from .025 inches to .043 inches.

CONCLUSIONS

Despite experimental problems with amplifier noise and the necessity to perform some calculations off-line, this project has proven the feasibility of correcting the Vatel blade clearance sensor output signal for speed effects. A peak sensing technique with time resolution of 0.16 microsecond has been demonstrated. With achievable noise reductions in the analog signal path this method should yield a tangential resolution of .002 inches, sufficient for the detection of blade vibration or twist at full speed on the example engine. With correct handling of A/D conversion results and the use of proper constants for the sensor being employed, it should be possible to achieve on-line speed compensation with a computed clearance precision of .0001 inches or better.

A double precision divide is essential to on-line calculation of clearance, so the selection of a microprocessor for future systems should take this requirement into account.

A great deal of time and effort could have been saved in troubleshooting and calibrating this system if an accurate electrical simulation for the once-per-revolution and blade signals had been arranged. It is impractical to debug software and find digital and analog signal processing hardware problems under the time and cost constraints of jet engine test cell operation.

FUTURE RESEARCH

The next step in this research should be to build a production prototype signal processing system with an improved first stage amplifier, using a microprocessor which will perform the required calculations on-line. With proper attention to the test and communications features of the new system, the gathering of data

on compressor blade clearance, vibration and twist should become practical in a wide variety of circumstances. For lowest cost of development and use, the new system should be designed as a microcomputer plug-in. This strategy will open up many possibilities for turbomachinery data acquisition and analysis at reasonable capital cost and with application flexibility. Compressor blade clearance control, vibration monitoring and similar uses of the data from Vatel sensors should then proceed. As high temperature versions of the sensor are developed, similar applications will become possible in turbines. The benefits of casing-based monitoring of turbomachinery blade conditions will then be broadly available and economical to acquire.

For convenience and economy in tests of the new system, an accurate electrical simulator for sensor and once-per revolution signals should be constructed. This simulator should have the flexibility to adjust the amplitudes and timing of individual signals, so that response of the tip clearance signal processor to anticipated signals can be determined before trials in the test cell environment.

A mechanical mockup of a turbomachine blade row with known variations in end gap should be constructed, preferably in a temperature-controlled chamber. This apparatus would be used to calibrate sensors and test signal processors, and to explore the effects of temperature on sensor calibration and operation.

The potential of blade vibration and twist monitoring should be explored using two or more sensors, together with processors whose timing is slaved or coordinated. One objective for such a combination would be to detect rotating stall. This should be explored experimentally in a compressor research facility.

REFERENCES

- (1) Wilson, D. S., "An Investigation of Sensors Suitable for Monitoring Blade Deflections for a VA1310 Wind Tunnel Compressor" - AFWAL-TR-81-3076 Final Report on Contract F33615-79-C-3019 July 1981
- (2) Kiraly, L. J., "Digital System for Dynamic Turbine Engine Blade Displacements" - Measurement Methods on Rotating Components of Turbomachinery, ASME Gas Turbine Symposium, New York, 1980
- (3) Wilson, D. S., "Compressor Blade Monitoring System for a VA1310 (Allis Chalmers) Wind Tunnel Compressor" - Final Report AFWAL Contract No. F33615-79-C-3019 July 1980
- (4) Barranger, J. P. and Ford, M. J., "Laser Optical Blade Tip Clearance Measurement System" - Measurement Methods on Rotating Components of Turbomachinery, ASME Gas Turbine Symposium, New York, 1980
- (5) Roth, H., "Vibration and Clearance Measurements on Rotating Blades Using Stationary Probes" - Measurement Techniques in Turbomachines, Von Karman Institute For Fluid Dynamics Lecture Series, May 18-22, 1981
- (6) O'Brien, W. F., Sparks, J. F. and Dellinger, D. F., "Non-Contacting Method for Measurement of Dynamic Blade Motions in Axial-Flow Compressors" - Proceedings of the 27th International Instrumentation Symposium, ISA, Indianapolis, IN, April 1981

```

10 REM
20 REM      BASIC INTERFACE PROGRAM                      HKK 5/9/88
30 REM THIS BASIC PROGRAM INTERFACES WITH THE ASPI DSP BOARD SOFTWARE.
40 REM IT WAITS FOR A KEY INPUT FROM THE PC KEYBOARD.  WHEN IT GETS ONE
50 REM IT SETS THE DOWNLOAD FLAG IN THE ASPI'S PROGRAM MEMORY.
60 REM WHEN THE O BLADE HAS PASSED, THEN THE 32010 SOFTWARE WILL STORE
70 REM ALL CURRENT TIME-OF-ARRIVAL VALUES AND A/D'ED AMPLITUDE VALUES
80 REM IN THE PROGRAM MEMORY.  THE 32010 WILL THEN RESET THE DOWNLOAD
90 REM FLAG INDICATING TO THE PC THAT THE DATA IS PRESENT AND CAN BE READ.
100 REM THE PC WILL THEN READ THE DATA, CALCULATE THE GAP CLEARANCES,
110 REM AND DISPLAY THE INFO FOR ALL 28 BLADES.
150 REM
151      K1 = 1.2E-08
152      K2 = .0001
153      K3 = .31
154      K4 = .02
155 REM K5 = 7.0E-05
156      INPUT "Enter K5, A/D output multiplier - ", K5
159      DEF SEG = 40960
160      CLS
170      LOCATE 22, 1
180      PRINT "Press any key to DOWNLOAD DATA..."
190 REM LOOP HERE UNTIL A KEY IS PRESSED
200      V$ = INKEY$
210      IF V$ = "" THEN 200
215      IF V$ = "S" THEN 495
220      CLS
230      LOCATE 3, 1
293      POKE 256, 1: POKE 257, 0
295      IF PEEK(256) + (256! * PEEK(257)) = 0 THEN 300
297      GOTO 295
300      SPDCNT = PEEK(370) + (256! * PEEK(371))
305      IF SPDCNT = 0 THEN SPEED = 0: GOTO 320
310      SPEED = 60 * (1 / (SPDCNT * 1.6E-07))
320      PRINT "TURBINE SPEED IS "; SPEED; " RPM"
330      PRINT ""
350      PRINT "      T-O-A", "GAP-IN./1000", , "      T-O-A", "GAP-IN./1000"
360      PRINT ""
370 REM LOOP WHERE VALUES ARE CALCULATED AND DISPLAYED
380      FOR I = 1 TO 14
390          TOA = PEEK(312 + (I * 2)) + (256! * PEEK(313 + (I * 2)))
400          AD = PEEK(256 + (I * 2)) + (256! * PEEK(257 + (I * 2)))
410          IF AD = 0 THEN GAP = 0: GOTO 430
420          GAP = ((K1 * SPEED ^ 2) - (K2 * SPEED) + K3) / (AD * K5) - K4
430          TOA2 = PEEK(340 + (I * 2)) + (256! * PEEK(341 + (I * 2)))
440          AD2 = PEEK(284 + (I * 2)) + (256! * PEEK(285 + (I * 2)))
450          IF AD2 = 0 THEN GAP2 = 0: GOTO 470
460          GAP2 = ((K1 * SPEED ^ 2) - (K2 * SPEED) + K3) / (AD2 * K5) - K4
463          IF I > 9 THEN 470
465          PRINT " "; I; "- "; TOA, GAP, , I + 14; "- "; TOA2, GAP2: GOTO
480
470          PRINT I; "- "; TOA, GAP, , I + 14; "- "; TOA2, GAP2
480      NEXT I
490      GOTO 170

```

Appendix A

```

10 REM
20 REM          BASIC INTERFACE PROGRAM                      HKK 5/9/88
30 REM THIS BASIC PROGRAM INTERFACES WITH THE ASPI DSP BOARD SOFTWARE.
40 REM IT WAITS FOR A KEY INPUT FROM THE PC KEYBOARD.  WHEN IT GETS ONE
50 REM IT SETS THE DOWNLOAD FLAG IN THE ASPI'S PROGRAM MEMORY.
60 REM WHEN THE 0 BLADE HAS PASSED, THEN THE 32010 SOFTWARE WILL STORE
70 REM ALL CURRENT TIME-OF-ARRIVAL VALUES AND A/D'ED AMPLITUDE VALUES
80 REM IN THE PROGRAM MEMORY.  THE 32010 WILL THEN RESET THE DOWNLOAD
90 REM FLAG INDICATING TO THE PC THAT THE DATA IS PRESENT AND CAN BE READ.
100 REM THE PC WILL THEN READ THE DATA, CALCULATE THE GAP CLEARANCES,
110 REM AND DISPLAY THE INFO FOR ALL 28 BLADES.
150 REM
151     K1 = 1.2E-08
152     K2 = .0001
153     K3 = .31
154     K4 = .02
155 REM K5 = 7.0E-05
156     INPUT "Enter K5, A/D output multiplier - ", K5
159     DEF SEG = 40960
160     CLS
170     LOCATE 22, 1
180     PRINT "Press any key to DOWNLOAD DATA..."
190 REM LOOP HERE UNTIL A KEY IS PRESSED
200     V$ = INKEY$
210     IF V$ = "" THEN 200
215     IF V$ = "S" THEN 495
220     CLS
230     LOCATE 3, 1
293     POKE 256, 1: POKE 257, 0
295     IF PEEK(256) + (256! * PEEK(257)) = 0 THEN 300
297     GOTO 295
300     SPDCNT = PEEK(370) + (256! * PEEK(371))
305     IF SPDCNT = 0 THEN SPEED = 0: GOTO 320
310     SPEED = 60 * (1 / (SPDCNT * 1.6E-07))
320     PRINT "TURBINE SPEED IS "; SPEED; " RPM"
330     PRINT ""
350     PRINT "      T-O-A", "GAP-IN./1000", , "      T-O-A", "GAP-IN./1000"
360     PRINT ""
370 REM LOOP WHERE VALUES ARE CALCULATED AND DISPLAYED
380     FOR I = 1 TO 14
390         TOA = PEEK(312 + (I * 2)) + (256! * PEEK(313 + (I * 2)))
400         AD = PEEK(256 + (I * 2)) + (256! * PEEK(257 + (I * 2)))
410         IF AD = 0 THEN GAP = 0: GOTO 430
420         GAP = ((K1 * SPEED ^ 2) - (K2 * SPEED) + K3) / (AD * K5) - K4
430         TOA2 = PEEK(340 + (I * 2)) + (256! * PEEK(341 + (I * 2)))
440         AD2 = PEEK(284 + (I * 2)) + (256! * PEEK(285 + (I * 2)))
450         IF AD2 = 0 THEN GAP2 = 0: GOTO 470
460         GAP2 = ((K1 * SPEED ^ 2) - (K2 * SPEED) + K3) / (AD2 * K5) - K4
463         IF I > 9 THEN 470
465         PRINT " "; I; "- "; TOA, GAP, , I + 14; "- "; TOA2, GAP2: GOTO
480
470         PRINT I; "- "; TOA, GAP, , I + 14; "- "; TOA2, GAP2
480     NEXT I
490     GOTO 170

```

Appendix A

```

0002      *
0003      * This TMS32010 Assembly Language Program allows the DSP
0004      * board from ATLANTA SIGNAL PROCESSOR to work in con-
0005      * junction with the Signal Interface Board to monitor the
0006      * speed and signal amplitude information from the VATELL
0007      * turbine sensor. The program is interrupt-driven and
0008      * reads and stores required information for downloading to
0009      * the PC host. A BASIC program in the PC takes the infor-
0010      * mation and calculates a blade-to-sensor clearance based
0011      * upon sensor signal amplitude and time-of-arrival data.
0012      * This particular Signal Interface board and software pro-
0013      * gram is designed to operate with a turbine having 28
0014      * blades and operating up to a maximum speed of 16,000 RPM.
0015      * Board timing is based upon a processor clock speed of 25
0016      * MHz.
0017      *
0018      * SYMBOLS - DATA MEMORY LOCATIONS USED *
0019      *
0020      0002 STATUS EQU >2          STORE STATUS DURING INTRPT.
0021      0003 ACH EQU >3          STORE ACC. HIGH DURING INT.
0022      0004 ACL EQU >4          STORE ACC. LOW " "
0023      0005 AROO EQU >5          STORE AUX. REG. 0 " "
0024      0006 ARO1 EQU >6          STORE AUX. REG. 1 " "
0025      0008 BLDPTR EQU >8        BLADE POSITION POINTER
0026      0009 INITFG EQU >9        INITIALIZING FLAG
0027      000A CLCFLG EQU >A        FLAG- START CALCULATION
0028      000B SPEED EQU >B        SPEED OF PREV. ROTATION
0029      000C CUMLTV EQU >C        CUMULATIVE TOTAL OF TIME
0030      000D PRVNDX EQU >D        PREV. INDEX VALUE
0031      000E ONEFLG EQU >E        ONE TIME AROUND FLAG
0032      000F DA EQU >F
0033      0010 LOPCTR EQU >10
0034      0011 CNTRED EQU >11        STORE READING OF COUNTER
0035      0012 INDEX EQU >12        CURRENT INDEX READING
0036      0013 TEMP1 EQU >13        TEMP. STORAGE LOCATIONS
0037      0014 TEMP2 EQU >14
0038      0015 TEMP3 EQU >15
0039      0016 ADRED EQU >16        TEMP. STORAGE OF A/D VALUE
0040      *
0041      002B ADO EQU >2B          A/D VALUE - 1ST BLADE AFTER
0042      * INDEX. 2BH THROUGH 46H CONTAIN A/D VALUES
0043      * FOR 28 BLADES
0044      0047 TOAO EQU >47          TIME OF ARRIVAL - 1ST BLADE
0045      * AFTER INDEX. 47H THROUGH 62H CONTAIN TIME
0046      * OF ARRIVAL FOR 28 BLADES
0047      0063 CNTRDO EQU >63        COUNTER VALUE WHEN BLADE
0048      * ARRIVES
0049      *

```

Appendix A

NO\$IDT 32010 FAMILY MACRO ASSEMBLER PC3.0 87.050 00:12:45 05-12-88
 DSP BOARD CONTROL PROGRAM 5/11/88 - DSP5 PAGE 0003

```

0092 0000
0093 0000
0094 0000
0095 0000
0096 0000
0072 0097 0000      DATA    0,0,0,0,0,0
0098 0000
0099 0000
009A 0000
009B 0000
009C 0000
0073 009D 0000      TOA      DATA    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
009E 0000
009F 0000
00A0 0000
00A1 0000
00A2 0000
00A3 0000
00A4 0000
00A5 0000
00A6 0000
00A7 0000
00A8 0000
00A9 0000
00AA 0000
00AB 0000
00AC 0000
00AD 0000
00AE 0000
00AF 0000
00B0 0000
00B1 0000
00B2 0000
0074 00B3 0000      DATA    0,0,0,0,0,0
00B4 0000
00B5 0000
00B6 0000
00B7 0000
00B8 0000
0075 00B9 0000      SPED      DATA    0
0076 00BA 0001      TOOSLO     DATA    1      FLAG TELLS PC RUNNING SLOW
0077
  
```

Appendix A

```

0079      * INIT - INITIALIZATION PART OF PROGRAM
0080      * PROGRAM INITIALIZATION BEGINS HERE. ALL REGISTERS
0081      * ARE INITIALIZED, CONSTANTS TRANSFERRED FROM PROG.
0082      * MEMORY TO DATA MEMORY
0083 0100      AORG >100          START PROGRAM ON PAGE 1
0084 0100 7F81  INIT  DINT
0085 0101 7F8B      SOVM          SET OVERFLOW MODE
0086 0102 6880      LARP 0
0087 0103 6E00      LDPK 0
0088 0104 F800      CALL NITLIZ    CALL SUBROUTINE TO INIT.
      0105 014A
0089      *
0090 0106 7137      LARK AR1,55     PRIMARY REGISTERS
0091 0107 7062      LARK ARO,>62   PUT IN REG. 1 # OF VALUES
      * OF DATA MEMORY          PUT IN REG. 0 TOP ADDRESS
0092      *
0093 0108 6880  LOPDAT LARP 0      MAKE SURE ARP = 0
0094 0109 3113      SAR 1,TEMP1    STORE CURRENT COUNT. VALUE
0095 010A 7E81      LACK >81      BASE ADDRESS OF DATA IN PROG.
0096 010B 6113      ADDS TEMP1     CALC. PROG. ADDRESS
0097 010C 6791      TBLR *-,1     READ DATA, STORE @ADDRESS
0098      * POINTED AT, DEC. ARO, CHANGE ARP=1
0099 010D F400      BANZ LOPDAT    IF AR1 NOT 0, GO BACK
      010E 0108
0100 010F 6880      LARP 0         RESET AUX.REG.PTR.
0101 0110 4E0F      OUT DA,PA6    SET VALID D/A LEVEL
0102 0111 7E01      LACK 1
0103 0112 5013      SACL TEMP1
0104 0113 4913      OUT TEMP1,PA1 SET ENABLE2 SO S/H WILL SAMP.
0105 0114 7E00      LACK 0        SET A/D INPUT LOW
0106 0115 5013      SACL TEMP1
0107 0116 4A13      OUT TEMP1,PA2
0108 0117 F900      B MAIN        GO TO MAIN LOOP
      0118 0130
0109      *

```

```

0111      * MAIN - MAIN PROGRAM LOOP
0112      *
0113 0130      AORG    >130
0114 0130 660A  MAIN    ZALS    CLCFLG      SEE IF NEED TO GO DO CALC.
0115 0131 FF00      BZ      NOCALC      IF FLAG=0, DON'T CALL SUB.
        0132 0135
0116 0133 F800      CALL    CALC      IF FLAG=1, GO FOR IT
        0134 0155
0117 0135 7E80  NOCALC  LACK    >80      ADDRESS OF DOWNLOAD FLAG
0118 0136 6713      TBLR    TEMP1
0119 0137 6613      ZALS    TEMP1
0120 0138 FF00      BZ      NODNLD
        0139 013F
0121 013A 6608      ZALS    BLDPTR
0122 013B FE00      BNZ     NODNLD
        013C 013F
0123 013D F800      CALL    DWNLD
        013E 0196
0124 013F 4113  NODNLD  IN      TEMP1, PA1
0125 0140 7E02      LACK    2
0126 0141 7913      AND     TEMP1
0127 0142 FE00      BNZ     NODNLD
        0143 013F
0128 0144 7E01      LACK    1
0129 0145 5013      SACL    TEMP1
0130 0146 4813      OUT     TEMP1, PA0
0131 0147 7F82      EINT
0132 0148 F900  LOOPIT  B      LOOPIT      GO AROUND AGAIN
        0149 0148
0133      *

```

```

0135      * SUBROUTINE NITLIZ - INITIALIZE
0136      *      THIS SUBROUTINE CAN BE CALLED FROM ANYWHERE IN
0137      *      THE PROGRAM. IT WILL INITIALIZE THE NECESSARY
0138      *      DATA MEMORY LOCATIONS FROM VALUES IN THE PROGRAM
0139      *      MEMORY. THIS IS DONE PRIOR TO STARTING TO READ
0140      *      FROM SCRATCH. IT WOULD BE NECESSARY TO CALL IT IF
0141      *      THE TURBINE IS RUNNING TOO SLOW TO GET PROPER
0142      *      VALUES.
0143 014A 7107 NITLIZ LARK AR1,>7      PUT IN REG. 1 # OF VALUES
0144 014B 700F      LARK ARO,>OF      PUT IN REG. 0 TOP ADDRESS
0145      *      OF DATA MEMORY
0146 014C 6880 MOVDAT LARP 0      MAKE SURE ARP = 0
0147 014D 3113      SAR 1,TEMP1      STORE CURRENT COUNT. VALUE
0148 014E 7E10      LACK >10      BASE ADDRESS OF DATA IN PROG.
0149 014F 6113      ADDS TEMP1      CALC. PROG. ADDRESS
0150 0150 6791      TBLR *-,1      READ DATA, STORE @ADDRESS
0151      *      POINTED AT, DEC. ARO, CHANGE ARP=1
0152 0151 F400      BANZ MOVDAT      IF AR1 NOT 0, GO BACK
      0152 014C
0153 0153 6880      LARP 0      RESET AUX.REG.PTR.
0154 0154 7F8D      RET
0155      *
  
```

```

0157      * CALC SUBROUTINE - SPEED ACCUMULATION AND CALCULATIONS
0158      * ARE DONE HERE. SET OR RESET TOOSLO FLAG.
0159      *
0160 0155 6608  CALC   ZALS   BLDPTR   GET POINTER TO T-O-A VALUES
0161 0156 FF00          BZ     ISOBLD   IF BLDPTR = 0, BRANCH
0157 016A
0162 0158 6880          LARP   0        SET AUX. REG. PTR. = 0
0163 0159 3808          LAR    0, BLDPTR  FETCH INDEX TO T-O-A NOS.
0164 015A 6898          MAR    *-       DECREMENT REGISTER TO PREV.
0165      * T-O-A LOCATION
0166 015B 3013          SAR    0, TEMP1   STORE TEMPORARILY
0167 015C 7E63          LACK   >63      CALC. ADDRESS TO PUT T-O-A
0168 015D 6113          ADDS   TEMP1     ADD PTR. TO 1ST LOC. ADDRESS
0169 015E 5013          SACL   TEMP1     STORE TEMPORARILY
0170 015F 3813          LAR    0, TEMP1   NOW PUT CALC. ADD. IN AR
0171 0160 6688          ZALS   *        FETCH TIME OF ARRIVAL DATA
0172 0161 5013          SACL   TEMP1     STORE INFO. TEMP.
0173 0162 7E63          LACK   >63
0174 0163 6108          ADDS   BLDPTR
0175 0164 5014          SACL   TEMP2
0176 0165 3814          LAR    0, TEMP2
0177 0166 6688          ZALS   *        FETCH LAST BLADE'S T-O-A
0178 0167 6313          SUBS   TEMP1     SUBTRACT LAST T-O-A FROM PREV
0179 0168 F900          B      AROUND    GO AROUND NEXT. FOR 0 BLADE.
0169 016C
0180 016A 6663  ISOBLD  ZALS   CNTRDO   FETCH T-O-A VALUE FOR 0 BLADE
0181 016B 637E          SUBS   CNTRDO+27 SUBTRACT T-O-A VALUE FOR 27
0182      * BLADE
0183      * IF WE'VE GOTTEN HERE, WE HAVE THE ELAPSED TIME BETWEEN
0184      * THE LAST T-O-A AND THE PRESENT IN THE ACCUMULATOR
0185 016C 610C  AROUND  ADDS   CUMLTV   ADD TO CUMULATIVE TOTAL
0186 016D 500C          SACL   CUMLTV   STORE BACK IN REG.
0187      * NOW INITIALIZE, SET INITFLG, ENABLE SAMPLE, AND TRY AGAIN
0188      * WOW! WE FINALLY GOT HERE. NOW WHAT? LET'S SEE, OH YEAH,
0189      * WE CAN NOW TEST FOR ONEFLG. IF SET, ENABLE SAMPLE AND GO
0190      * BACK.
0191 016E 7E47  ACCISO  LACK   >47
0192 016F 6108          ADDS   BLDPTR   STORE ACCUMULATED TIME IN
0193 0170 5013          SACL   TEMP1    T-O-A DATA LOCATION
0194 0171 3813          LAR    0, TEMP1
0195 0172 660C          ZALS   CUMLTV   FETCH DATA
0196 0173 5088          SACL   *
0197 0174 6608          ZALS   BLDPTR   IF 0 BLADE, SPEED=CUMLTV &
0198 0175 FE00          BNZ    NTOBLD   CUMLTV=0
0176 017E
0199 0177 660C          ZALS   CUMLTV
0200 0178 500B          SACL   SPEED
0201 0179 7EB9          LACK   >B9     WRITE SPEED TO PROGRAM MEMORY
0202 017A 7D0B          TBLW   SPEED
0203 017B 7E00          LACK   0
0204 017C 500C          SACL   CUMLTV
  
```

Appendix A

0205	017D	5047	SACL	TOAO	SET TOA FOR 0 BLADE=0
0206			* SEE IF A/D DONE BEFORE READING		
0207	017E	F600	NTOBLD	BIOZ	ADDONE
	017F	0182			IF BIO LOW, A/D IS DONE
0208	0180	F900	B	NTOBLD	IF HIGH, GO AROUND UNTIL DONE
	0181	017E			
0209	0182	4616	ADDONE	IN	ADRED, PA6
0210	0183	7E01	LACK	1	READ A/D CONVERTER
0211	0184	5013	SACL	TEMP1	CAN RELEASE SAMPLE/HOLD NOW
0212	0185	4913	OUT	TEMP1, PA1	GOT IT
0213	0186	7E00	LACK	0	RESET CALCULATION FLAG
0214	0187	500A	SACL	CLCFLG	
0215			* FIRST HAVE TO GET A/D VALUE IN FORM WE CAN USE IN CALC.		
0216	0188	7E19	LACK	>19	
0217	0189	6713	TBLR	TEMP1	FETCH FFFF MASK FOR XOR'ING
0218	018A	6613	ZALS	TEMP1	
0219	018B	7816	XOR	ADRED	DO 1'S COMPLEMENT
0220	018C	5016	SACL	ADRED	
0221	018D	2C16	LAC	ADRED, 12	SHIFT RIGHT 4 TIMES
0222	018E	5816	SACH	ADRED	
0223			* STORE THIS NUMBER IN INDEXED FILE FOR A/D VALUES		
0224	018F	7E2B	LACK	>2B	
0225	0190	6108	ADDS	BLDPTR	DEVELOP INDEX FROM BLADE NO.
0226	0191	5013	SACL	TEMP1	
0227	0192	3813	LAR	0, TEMP1	PUT INDEX INTO AUX. REG.
0228	0193	6616	ZALS	ADRED	
0229	0194	5088	SACL	*	STORE IT NOW
0230	0195	7F8D	RET		ALL DONE, GO BACK NOW
0231			*		

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0233      * DOWNLOAD SUBROUTINE - DOWNLOAD TIME OF ARRIVAL AND
0234      * CLEARANCE INFORMATION TO PC. THE DOWNLOAD FLAG HAS BEEN
0235      * SET, THAT'S WHY WE'RE HERE. TRANSFER T-O-A'S AND A/D
0236      * DATA TO PROG. MEMORY, RESET DOWNLOAD FLAG AND RET
0237      *
0238 0196 7137 DWNLD LARK AR1,55 PUT IN REG. 1 # OF VALUES
0239 0197 7062 LARK ARO,>62 PUT IN REG. 0 TOP ADDRESS
0240      * OF DATA MEMORY
0241 0198 6880 LPDAT LARP 0 MAKE SURE ARP = 0
0242 0199 3113 SAR 1,TEMP1 STORE CURRENT COUNT. VALUE
0243 019A 7E81 LACK >81 BASE ADDRESS OF DATA IN PROG.
0244 019B 6113 ADDS TEMP1 CALC. PROG. ADDRESS
0245 019C 7D91 TBLW *-,1 WRITE DATA TO PROG. ADDRESS
0246      * POINTED AT, DEC. ARO, CHANGE ARP=1
0247 019D F400 BANZ LPDAT IF AR1 NOT 0, GO BACK
019E 0198
0248 019F 6880 LARP 0 RESET AUX. REG. PTR.
0249 01A0 7EB9 LACK >B9 STORE SPEED READING
0250 01A1 7DOB TBLW SPEED
0251 01A2 7E00 LACK 0
0252 01A3 5013 SACL TEMP1 RESET DOWNLOAD FLAG
0253 01A4 7E80 LACK >80
0254 01A5 7D13 TBLW TEMP1
0255 01A6 7F8D RET
0256      *
  
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0258      * CLEAR SUBROUTINE - CLEARS TIME OF ARRIVAL AND CLEARANCE
0259      *   VALUES IN DATA MEMORY. CALLED WHEN INITIALIZING AND
0260      *   WHEN LOOP COUNTER DECREMENTS OUT.
0261      *
0262 01A7 7137 CLEER  LARK  AR1,55      PUT IN REG. 1 # OF VALUES
0263 01A8 7062      LARK  ARO,>62     PUT IN REG. 0 TOP ADDRESS
0264      *                               OF DATA MEMORY
0265 01A9 6880 LPDAT1 LARP  0          MAKE SURE ARP = 0
0266 01AA 3113      SAR    1,TEMP1     STORE CURRENT COUNT. VALUE
0267 01AB 7E81      LACK    >81        BASE ADDRESS OF DATA IN PROG.
0268 01AC 6113      ADDS    TEMP1       CALC. PROG. ADDRESS
0269 01AD 6791      TBLR    *-,1       READ DATA, STORE @ADDRESS
0270      *                               POINTED AT, DEC. ARO, CHANGE ARP=1
0271 01AE F400      BANZ    LPDAT1      IF AR1 NOT 0, GO BACK
      01AF 01A9
0272 01B0 6880      LARP    0          RESET AUX.REG.PTR.
0273 01B1 7F8D      RET
0274      *

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0276      * CLRPRG - CLEAR PROGRAM MEMORY SUBROUTINE
0277      *   THIS SUB. CLEARS THE T-O-A AND CLEARANCE VALUES IN THE
0278      *   PROGRAM MEMORY LOCATIONS TO 0.  DONE WHEN SPEED TOO SLOW
0279      *
0280 01B2 7E00 CLRPRG LACK 0          0 INTO ACC.
0281 01B3 5014      SACL TEMP2      STORE 1N TEMPORARY REGISTER
0282 01B4 7138      LARK AR1,56     PUT IN REG. 1 # OF VALUES
0283 01B5 6881 LPDAT2 LARP 1        MAKE SURE ARP = 1
0284 01B6 3113      SAR 1,TEMP1     STORE CURRENT COUNT. VALUE
0285 01B7 7E81      LACK >81        BASE ADDRESS OF DATA IN PROG.
0286 01B8 6113      ADDS TEMP1       CALC. PROG. ADDRESS
0287 01B9 7D14      TBLW TEMP2      READ DATA, STORE @ADDRESS
0288      *                               POINTED AT, DEC. AR1
0289 01BA F400      BANZ LPDAT2      IF AR1 NOT 0, GO BACK
      01BB 01B5
0290 01BC 6880      LARP 0          RESET AUX.REG.PTR.
0291 01BD 7E01      LACK 1
0292 01BE 5013      SACL TEMP1      SET TOOSLO FLAG FOR PC
0293 01BF 7EBA      LACK >BA
0294 01C0 7D13      TBLW TEMP1
0295 01C1 7F8D      RET
0296      *

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0298      *
0299      *
0300 01C2 7C02 INTRPT SST STATUS 1 STORE STATUS ON PAGE 1
0301 01C3 6E01      LDPK 1 1 SET DATA PAGE = 1
0302 01C4 5803      SACH ACH 1 STORE ACCUMULATOR
0303 01C5 5804      SACH ACL 1
0304 01C6 3005      SAR 0, AROO 1 STORE AUX. REGISTERS
0305 01C7 3106      SAR 1, ARO1 1
0306 01C8 6E00      LDPK 0 1 DATA PAGE PTR. = 0
0307      *
0308 01C9 7E00      LACK 0 1 HURRY UP AND HOLD S/H SO
0309      *      WON'T LOSE DATA
0310 01CA 5013      SACL TEMP1 1
0311 01CB 4913      OUT TEMP1, PA1 2 GOT IT
0312 01CC 4813      OUT TEMP1, PA0 FIX SO CAN HAVE NO MORE INT.
0313 01CD 7E01      LACK 1 TO SETTLE
0314 01CE 5013      SACL TEMP1 PULSE THE A/D TO START IT
0315 01CF 4A13      OUT TEMP1, PA2
0316 01D0 7E00      LACK 0
0317 01D1 5013      SACL TEMP1
0318 01D2 4A13      OUT TEMP1, PA2 480 nSEC PULSE
0319 01D3 4011      IN CNTRED, PA0 GET TIME-OF-ARRIVAL DATA
0320 01D4 6880      LARP 0
0321      *
0322      * THIS IS A REGULAR TRIP THROUGH THE INTERRUPT ROUTINE
0323      *
0324 01D5 7E01      LACK 1 INCREMENT BLADE POINTER
0325 01D6 6108      ADDS BLDPTR
0326 01D7 5008      SACL BLDPTR PUT BACK IN REGISTER
0327 01D8 660D      ZALS PRVNDX TEST TO SEE IF THE INDEX AT
0328      * LAST INTERRUPT WAS A 0
0329 01D9 FE00      BNZ PNDXNO IF NOT, GO ON
      01DA 01E7
0330      * IF YOU GOT HERE, PREVIOUS INDEX WAS 0
0331 01DB 4112      IN INDEX, PA1 FETCH INDEX INFO. TO SEE IF
0332      * INDEX IS PRESENTLY A 0
0333 01DC 7E01      LACK 1 MASK ALL BUT LSB
0334 01DD 7912      AND INDEX AND WITH ACC.
0335 01DE 5012      SACL INDEX
0336 01DF 500D      SACL PRVNDX MAKE PRVNDX = INDEX
0337 01E0 FF00      BZ NDXSLO IF INDEX STILL 0, GO ON
      01E1 01EC
0338      * INDEX HAS CHANGED FROM 0 TO 1, THEREFORE SET BLADE PTR.
0339      * TO 0 AND GO ON
0340 01E2 7E00      LACK 0
0341 01E3 5008      SACL BLDPTR
0342 01E4 500E      SACL ONEFLG RESET ONE TIME AROUND FLAG
0343      * IF SET
0344 01E5 F900      B NDXSLO GO AROUND NEXT BECAUSE IT'S
      01E6 01EC
0345      * Appendix A FOR PRVNDX = 1

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0316	01E7	4112	PNDXNO	IN	INDEX, PA1	SET PRVNDX = INDEX, WHETHER
0347	01E8	7E01		LACK	1	INDEX HAS CHANGED FROM 1 TO
0348	01E9	7912		AND	INDEX	0 OR NOT
0349	01EA	5012		SACL	INDEX	
0350	01EB	500D		SACL	PRVNDX	
0351	01EC	7E01	NDXSLO	LACK	1	SET CALC. FLAG SO WE WILL
0352	01ED	500A		SACL	CLCFLG	KNOW TO DO THEM
0353			*			
0354			*			
0355	01EE	7E1C	RESTOR	LACK	28	TEST TO SEE IF GONE OVER 27
0356	01EF	6308		SUBS	BLDPTR	BLADES DUE TO NOISE
0357	01F0	FE00		BNZ	NOTOVR	IF ACC. NOT 0, NOT OVER
	01F1	01F9				
0358	01F2	7E1B		LACK	27	
0359	01F3	5008		SACL	BLDPTR	
0360	01F4	7E00		LACK	0	
0361	01F5	500A		SACL	CLCFLG	
0362	01F6	6880		LARP	0	
0363	01F7	F900		B	ISOVR	
	01F8	0200				
0364	01F9	6880	NOTOVR	LARP	0	
0365	01FA	7E63		LACK	>63	CALC. ADDRESS TO PUT T-O-A
0366	01FB	6108		ADDS	BLDPTR	ADD PTR. TO 1ST LOC. ADDRESS
0367	01FC	5013		SACL	TEMP1	STORE TEMPORARILY
0368	01FD	3813		LAR	0, TEMP1	NOW PUT CALC. ADD. IN AR
0369	01FE	6611		ZALS	CNTRED	FETCH TIME OF ARRIVAL DATA
0370	01FF	5088		SACL	*	STORE INFO.
0371	0200	7F9D	ISOVR	POP		PUSH STARTING ADDRESS OF MAIN
0372	0201	7E01		LACK	>1	LOOP ON STACK
0373	0202	5013		SACL	TEMP1	
0374	0203	7E30		LACK	>30	
0375	0204	0813		ADD	TEMP1, 8	
0376	0205	7F9C		PUSH		
0377			* CAN GO ON NOW			
0378	0206	6E01		LDPK	1	SET DATA PAGE = 1 IF MOD.
0379	0207	3805		LAR	0, ARO0	LOAD AUX. REG. WITH OLD VAL.
0380	0208	3906		LAR	1, ARO1	
0381	0209	6503		ZALH	ACH	LOAD ACC. WITH OLD VALUE
0382	020A	6104		ADDS	ACL	ADD IN LOW ORDER 16 BITS
0383	020B	7802		LST	STATUS	RESTORE STATUS
0384	020C	6E00		LDPK	0	
0385	020D	7F81		DINT		DON'T ENABLE INTERRUPTS YET
0386	020E	7F8D		RET		
0387			*			
0388				END		

NO ERRORS, NO WARNINGS
 ^Z

CERTIFICATION OF TECHNICAL DATA CONFORMITY

The Contractor, VateLL Corporation, hereby certifies that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. F33615-87-C-2802 is complete, accurate, and complies with all requirements of the contract.

24 May 1988
Date

Lawrence W. Langley
Lawrence W. Langley, President

ABSTRACT

A signal processing system was designed and constructed to detect peaks of the VateLL eddy current clearance sensor signal, measure their amplitude and timing, and compute a correction for machine speed to indicate clearance and time of arrival. The system is based on an ADP1BM301 signal processing plug-in for the PC/XT, and consists of a second plug-in, along with special software for signal detection and processing. Tests on a Pratt and Whitney JT15D first stage fan demonstrated timing precision of 0.16 μ second and indicated individual blade clearances. A capability to perform the speed correction calculation and indicate blade clearance continuously in real time is projected, based on the test results.