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TURBOJET BLADE VIBRATION DATA ACQUISITION DESIGN AND FEASIBILITY TESTING

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16. Abstract

A turbojet blade vibration data acquisition system was designed to allow the measurement of blade vibration in a non-contact manner. This report describes the data acquisition system utilizing 96 microprocessors to gather data from optical probes, store, sort and transmit to the central computer. Areas of high technical risk were identified and a two-microprocessor system was breadboarded and tested to investigate these areas. Testing showed that the system was feasible and that low technical risk would be involved in proceeding with the complete system fabrication.

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SUMMARY

The objective of the program conducted by Shaker Research Corporation was to test the feasibility of expanding an optical method of detecting turbojet blade vibration from a single port system to a multiport system that allows high frequency response measurements to be made. The system was designed and breadboarded. It included the control function and two Data Acquisition Modules simulating a two-port system. This report describes the measurement concept and the design approach utilized.

The areas of technical risk in the system were identified and a test plan was conducted that investigated each area of risk. The results of the testing showed that the system was capable of operating as planned and therefore the technical risk involved in constructing the complete system would be small. This report, therefore, recommends that the complete measurement system be fabricated and installed at NASA - Lewis.

INTRODUCTION

The detection of the onset and the study of the character of turbojet blade flutter in gas turbine test programs is extremely important to the reliable development of these engines. Traditionally these measurements have been made using strain gages attached to the rotating blading with the signals brought out through slip ring assemblies. Problems associated with these kinds of measurements have led NASA-Lewis personnel to investigate an optical approach to making the measurement. (Ref. 1). Initial success was reported for the optical technique and work is continuing at NASA-Lewis on further development of the measurement system. This work involves observing all blade tips as they pass a single fixed optical probe.

A more ambitious program was also initiated at NASA-Lewis that involved obtaining data from many ports spaced around the circumference of a test rig, or ultimately, an engine. This technique relies upon a fiber optic system to detect the presence of a blade by detection of light reflected from the blade tip. Blade deflection can be determined by measuring the time at which a blade passes the fixed optical probes. The actual deflection is directly proportional to the difference between actual and predicted (vibrationless) blade passage times. With enough sensors located around the circumference of the rotor case, the data system can measure blade tip motion equivalent to measurements obtained by analog to digital sampling of sensors mounted on each blade tip.

Obviously in constructing such an instrumentation system there are several areas of technical risk which if not successfully surmounted could result in a useless and expensive data system. Recognizing this fact, NASA wisely decided to split the development program into two parts. In part one, the system would be designed. As part of the design, a critical review would be made of those portions of the system that involved the greatest risk. Enough of the system would then be breadboarded to allow feasibility testing to be conducted and the risk elements to be evaluated. This report covers the part one effort. Testing has resolved the uncertainties of the system operation satisfactorily, and the second part of the work -- building the complete system -- can be undertaken with a high level of confidence.

MEASUREMENT DESCRIPTION

CONCEPT

The objective of the measurement is to determine turbojet blade tip vibration motion by using fixed probes. The measurement requires a precise knowledge of angular position of the rotor at any instant of time and a signal generated when a blade passes an exact location on the engine case. Fig. 1 is a simplified concept. If the sensor "sees" the blade when the angular position is exactly θ, then the blade is not deflected at that instant. If the sensor "sees" the blade when the angular position is different than θ (is $\theta \pm \alpha$), then the actual deflection of the blade at that instant may be calculated from the value α and the compressor stage geometry.

The sensor that has been successfully applied consists of a bifurcated fiber optic bundle that provides both a light source and a return path to a receiver that looks for the reflection of light from the blade tip as it passes by the optical bundle. Also a pair of pulse generators are used in tandem to generate a constant number of pulses per rotor revolution. Angular position is determined from the number of pulses counted after the 1/rev. signal. The pulse train could be generated by a gear or more accurately by an encoder of some type mounted to the shaft. All encoder concepts, however, suffer either from inaccuracies of their own or inability to generate enough pulses per revolution to obtain the desired blade motion resolution. A previously proposed solution to this problem is to measure the time interval between 1/rev. signals and compute a frequency that would produce the desired number of pulses per revolution. This computed frequency would then be "dialed" into an accurate frequency synthesizer. In this manner thousands of accurately spaced pulses may be generated for one shaft revolution. This train of pulses is now called the angle clock pulse train. For now, let's assume that the rpm remains constant. The actual method used to overcome rpm variation will be described in the section on system design.

Next, instead of one sensor, or port, suppose several ports are equally spaced around the circumference of the engine. If the engine is now operated in a condition in which the blades are not vibrating, the count when each blade arrives at each port can then be memorized for this zero deflection case. As the blades begin to vibrate, the arrival count can again be stored at each port for each blade. After the test, these counts may be recalled, subtracted from the zero deflection run count, converted to blade tip motion and could be plotted as shown in fig. 2. Each dot is the deflection at a given port. The data may be sorted to produce the time varying history of one blade. If data from many revolutions are saved, a Fast Fourier Transform (FFT) may be calculated to obtain the amplitude and frequency of each of the blade flutter components.

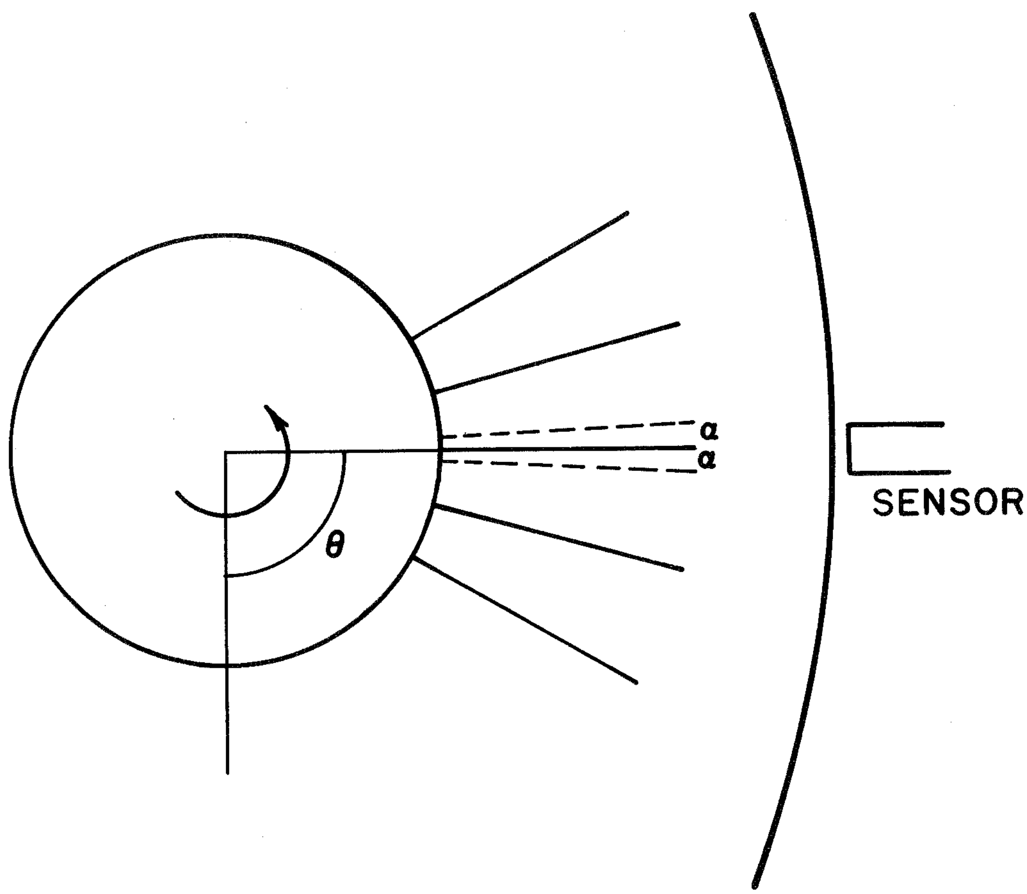


Fig. 1 Simplified Measurement Concept

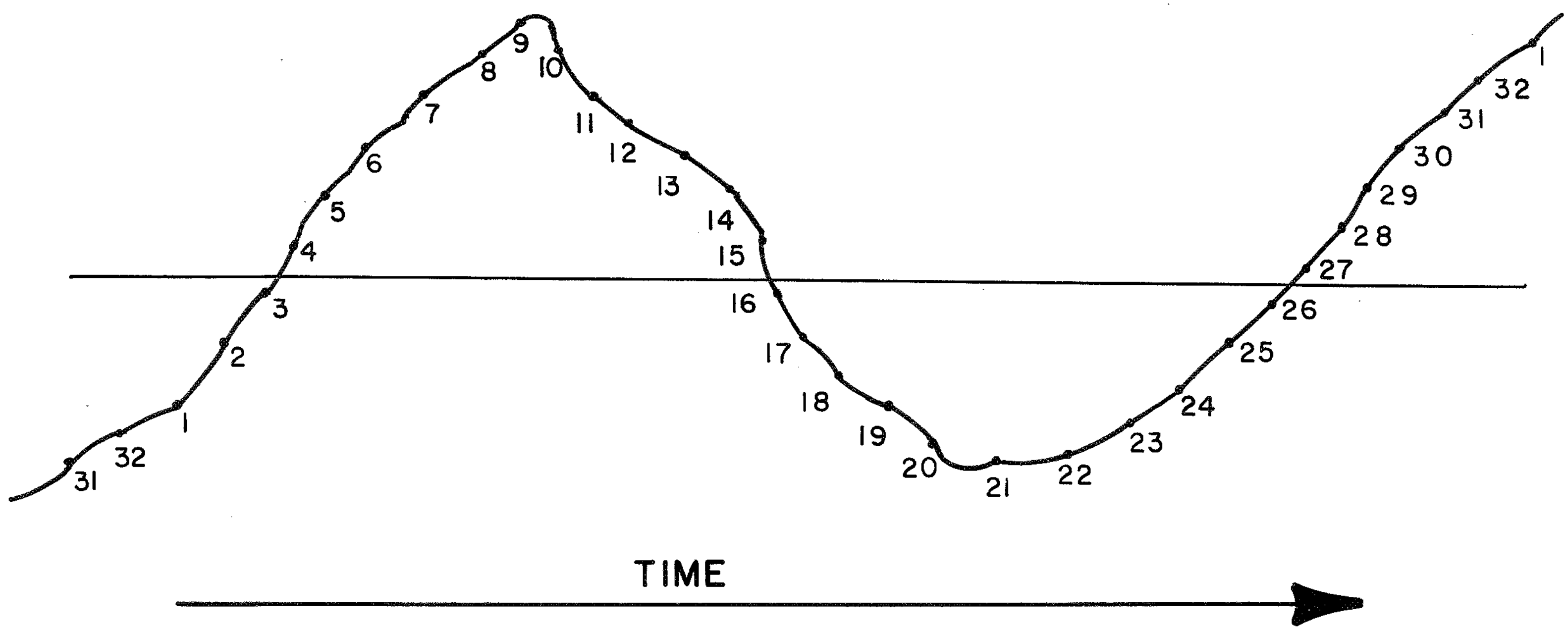


Fig. 2 Reconstructed Time Domain Vibration Signal

An additional factor which complicates the measurement must now be considered. Blade flutter and vibration can occur in more than one mode. For example, one flutter component might be simple blade bending. In this case, one sensor per port would completely define the blade motion. Fig. 3 shows this typical motion. Blade flutter may however also contain torsional or blade camber line deflection components. These latter two types of flutter are shown in figs. 4 & 5. Many sensors are needed in order to measure how all of the vibrating blades are deforming.

In order to handle the vast amount of numbers that will be generated at each port for each sensor, a system approach was conceived where each sensor would be monitored by a microprocessor with a 4k memory. All microprocessors would be tied together to a central controller for ease in setting up the test parameters and organizing and displaying the results. The data stored may be used to calculate a Fast Fourier Transform (FFT) to obtain the vibration components of the blades. In conventional vibration measurement systems where one transducer is used and the analog output is digitized by an A/D converter, important variables are the digitizing rate and the memory length. In the measurement concept being developed here, the same variables are important in determining the maximum frequency and resolution for the FFT. The digitizing rate in this system is the reciprocal of the time it takes one blade to go from one sensor to the next. The memory length appears to be fixed.

If the microprocessors are linked to each other as well as to the central processor, then additional flexibility may be built into the measurement system. Assume that the number of ports is initially chosen so that the blade passage time from port to port yields a digitizing rate that results in a maximum frequency of the FFT higher than the highest vibrational component expected. The digitizing rate may be varied by varying the speed of the rotor. Another method would be to use every other port so that the digitizing rate would be reduced. Frequency resolution may be improved if the memory length can be increased and this can be accomplished if the system allows the use of 4k of memory associated with the unused port. Sampling rate may be left at the higher rate if all ports are used and resolution may be increased if data is not taken for every blade but only, for example, every other or every third blade.

To achieve additional flexibility in the digitizing rate and memory length, the measurement system must be capable of operating in two variations of the basic operation where data is taken from each blade at each port. These variations are:

1. The system must have the ability to take data from every port or every other port, or from every fourth port and to utilize the memory associated with the unused ports for data storage.

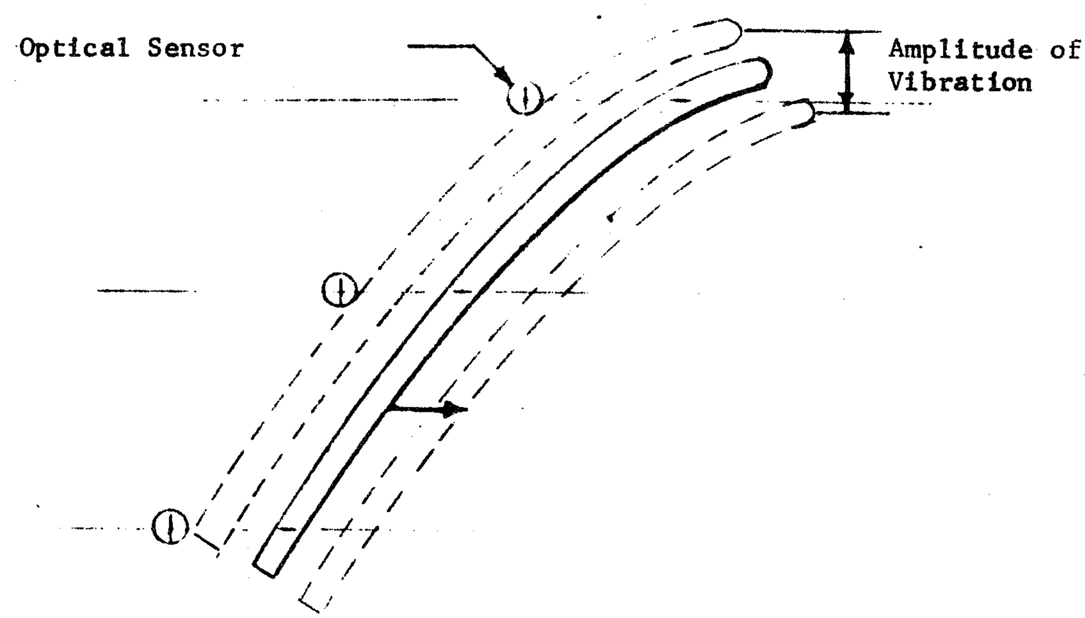


Fig. 3 Blade Bending Motion

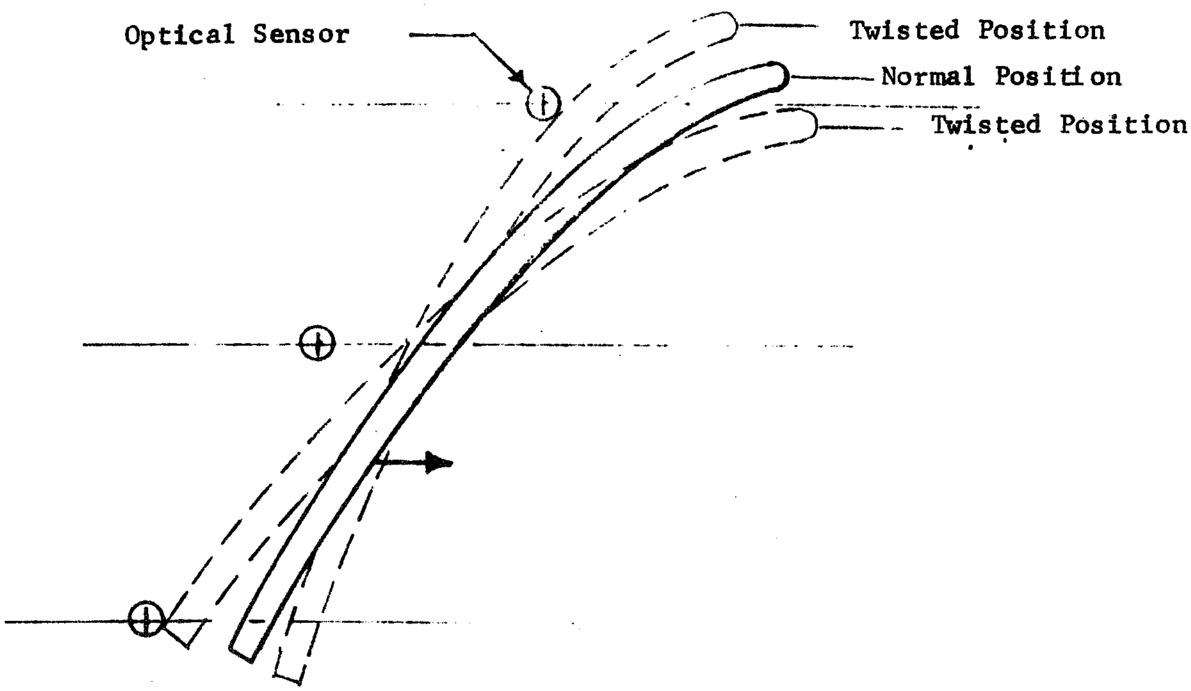


Fig. 4 Blade Twist Motion

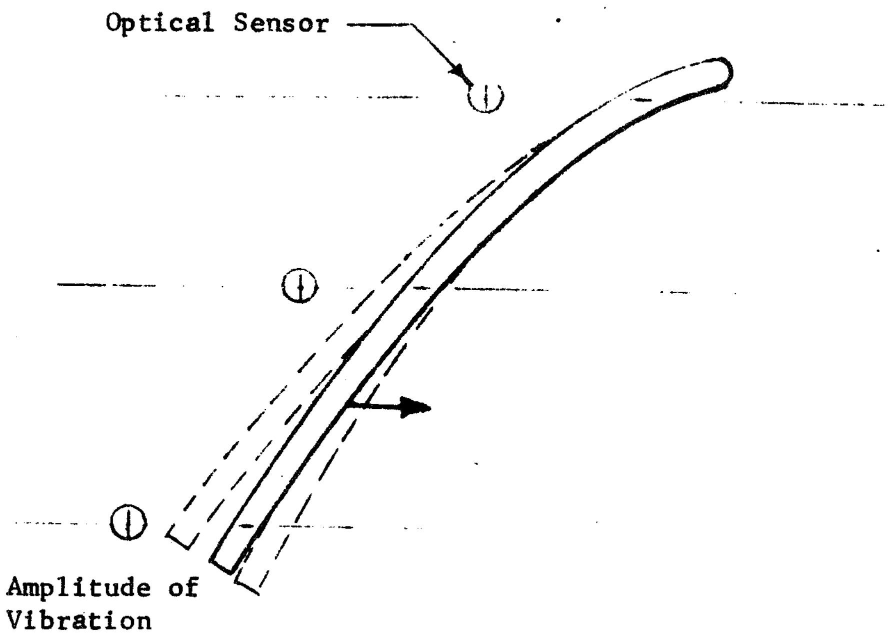


Fig. 5 Blade Camber Line Deflection

2. The system must have the ability to take data from every blade or to skip any number of blades while taking data.

3. A combination of the above two operations.

The measurement system proposal would utilize 8 bit microprocessors since these processors appeared to have the required speed and were available when the concept was originally developed.

SPECIFICATIONS

The measurement system designed must be capable of operation with a wide variety of rotors; however, a sample rotor specification was developed and made part of the contract. These are as follows:

Rotor diameter	508 mm (20 inch)
Rotation rate	1 885 rad/s (1800 RPM)
Blade tip thickness	0.508 mm (0.020 inch)
Blade tip width	25.4 mm (1.0 inch)
Maximum rotor blade vibration frequency	3 500 Hz
No. of blades in rotor	64

The requirement for maximum system resolution would equate one count bit equal to 0.020 mm (0.008 inch) deflection while the minimum resolution would be 1 bit equals 0.254 mm (0.01 inch).

If the above rotor specification and resolutions are used, the following measurement parameters may be developed.

Tip speed at 1 885 rad/s	=	478.78 m/s (18 850 inch/sec)
	=	108 000°/s

Maximum Resolution

0 to 0.0008 inch corresponds to 1 bit resolution

Full scale	=	± 2.6 mm (± 0.1024 inch) (7 bits plus sign)
	=	± 0.587°
Time resolution	=	42.4 ns

Nominal angle clock frequency	=	23.56 mHz
Nominal synthesizer Multiplication factor (X 1/rev.)	=	78 533

Minimum Resolution

0 to 0.254 mm corresponds to 1 bit resolution

Full scale	=	± 32.51 mm (1.28 inch)
	=	± 7.33°
Time resolution	=	530.5 ns
Nominal angle clock frequency	=	1.88 mHz
Nominal synthesizer multiplication factor	=	6 280

An error can be associated with the end of a revolution since at this point, the one per rev signal resets the angle clock counter. At a given port, a blade may be passing at this same time and for one revolution it could pass just before the reset while the next revolution it could pass just after. The blade deflection could be small between the two cases but could appear large due to resetting the counter. For example, in one revolution the count could be 100. In the next revolution, the reset could come at count 102 and the blade arrive at a count of 2. This is actually only a deflection of a count of 4 but would appear as 98. To minimize this possible error, the count should be approaching 256 at the time of reset. If the synthesizer multiplication factor is allowed to be only multiples of 256, this would result in zero error for zero speed drift. This modifies actual full scale settings as shown below.

Nominal Full Scale	X Factor	Angle Clock Frequency	Actual Full Scale
± 2.601 mm	307 x 256 78 592	23,578 mHz	± 2.603 mm
± 32.51 mm	25 x 256	1.92 mHz	± 31.92 mm

These values are for the specification rotor. If the rotor geometry, speed or resolution requirements change, angle clock frequencies will also change. The number of ports used is directly related to the sampling rate and thus the frequency response of the system. Consider the specification rotor maximum rotor blade vibration frequency of 3 500 Hz along with its rotational speed of 1 885 rad/s (18 000 rpm). To produce a FFT with a maximum frequency of 3 500 Hz, a sampling rate at least twice this frequency is required or 7 000 Hz. The period of this sampling rate is 142 μsec and must be equal to the time for one blade to go from one sensor to the next. The rotor travels 0.268 radians in 142 μsec which means that there should be a mimumum of 24 ports around the circumference of the rotor case. Aliasing errors (equivalent to stroboscopic effect in the single port system) would result if a higher frequency than 3 500 Hz were in the data. The desire for a safety factor as well as a desire to have the number of ports a power of 2 results in a 32 port system. If the case of 32 ports and a memory capacity of 4 096 8 bit words at each port is used, then the following frequency responses and resolutions may be obtained:

32 ports, 64 blades, 1 885 rad/s

Sample time and rate (time for blade n to get from port N to port (N+1)	t = 104 μsec f = 9 600 Hz
Memory length/blade (Memory X ports/ blades)	2 048
Time to fill memory	t = 0.213 s
Frequency resolution (1/T) (1 024 line FFT)	4.69 Hz
Max frequency (9 600/2 or 4.69 x 1 024)	4 800 Hz

This frequency response exceeds the maximum rotor blade vibration frequency of the specification. Extreme care must be taken to insure that frequency components higher than 4 800 Hz are not present in the data since they will cause aliasing errors. In this type of system, there are not ways to produce the equivalent of an anti-aliasing filter.

Other combinations of number of ports, number of blades and rotor speed are included in Table 1.

MEASUREMENT PROBLEM

In the design of the measurement system, several critical areas must be addressed if the system is to succeed. A brief explanation of the problems is given below. The solution to these problems will be covered in the explanation of the design.

Angular Position Information. The key to the successful measurement of blade tip motion is the precise knowledge of the angular position of the rotor when a blade arrival pulse is received at a given port. The resolution of the angular position must also be variable to allow the measurement of blade tip motion to different resolutions within the 8 bits available. Based on the specification, the number of pulses per revolution will vary from 78 592 to 6 400 for full scale blade tip motion from ± 1.88 mm and ± 32.51 mm. The maximum pulse rate corresponds to the frequency of 23 578 mHz. This means that the transmission of the angle clock pulse train to the data acquisition modules at each port is not a trivial problem. Additionally, if the rotor speed changes, the angle clock frequency must change to continue to produce 78 592 pulses per revolution. The frequency change must occur between two clock pulses (or in a minimum of 42 ns) or at least change smoothly in a time not much longer -- without spurious pulse bursts or long times with no pulse output.

Keeping Track of the Proper Blade. The secret to obtaining a high frequency response measurement of blade deflection is to sample blade deflections at each port as the blade passes. This means that to assembly the sampled time domain signal for a given blade, data for that blade must be gathered from the memory located at each port. This implies that the data is placed in memory in an orderly, predetermined manner. Two very important considerations are: 1) the identification of data for the first blade in each memory; and 2) the elimination of any extra or missing data points which would completely destroy the integrity of data points following. The first blade is a problem since except for a few combinations of numbers of rotor blades and numbers of ports, one blade will always be very close to a port sensor. Then depending on whether the blade is deflected backward or forward at the starting instant it may or may not be the first blade for which data is taken.

TABLE I

EVALUATION OF SYSTEM PERFORMANCE

System characteristics for different experiment setups.

Experiment Setup	32 Ports 64 Blades 1 885 rad/s [1]	16 Ports 64 Blades 1 885 rad/s [1]	32 Ports 32 Blades 1 885 rad/s	32 Ports 64 Blades 942.5 rad/s	16 Ports 32 Blades 1 885 rad/s	32 Ports 64 Blades 3 770 rad/s
Sample Time	104 μsec	208 μsec	104 μsec	208 μsec	208 μsec	52 μsec
Sample Frequency	9 600 Hz	4 800 Hz	9 600 Hz	4 800 Hz	4 800 Hz	19 200 Hz
Memory/Blade	2 048	2 048	4 096	2 048	4 096	2 048
Time to Fill Memory	0.213 s	0.426 s	0.426 s	0.426 s	0.852 s	0.106 s
Frequency Resolution	4.69 Hz	2.35 Hz	2.35 Hz	2.35 Hz	1.17 Hz	9.4 Hz
Max Frequency	4 800 Hz	2 400 Hz	4 800 Hz	2 400 Hz	2 400 Hz	9 600 Hz
FFT (lines)	1 024	1 024	2 048	1 024	2 048	1 024

[1] All conditions are taken for a system using 32 ports and the specification rotor. Lesser ports imply skipping ports while lesser blades imply skipping blades. Smaller number of ports mean additional memory.

Microprocessor Timing. The microprocessor that will be used to handle the data at each port must be carefully selected and the critical loop coded. Options must be included that pass data on to the next module as well as the ability to skip blades. At 1 885 rad/s and 64 blades, the time between two undeflected blades arriving at a port is 52 μs. Less than this time could be available depending on the relative deflection of the blades as they arrive at a port.

Feasibility Testing. The concluded contract work included the controlled testing at two data acquisition modules with simulated blade pass signals in order to prove the feasibility of a full scale system for making the blade flutter measurement. The system built in this breadboard phase lent itself to this testing and the testing was conducted which proved feasibility.

SYSTEM DESIGN

This section will describe the complete measurement system. The next section will describe the breadboard system and the feasibility testing.

Conceptual Design

In order to describe the conceptual basis for the machine, consider fig. 6 which shows a hypothetical six-bladed wheel and a system utilizing four sensor ports. If at time zero, all ports were commanded to start taking data then it might be expected that for port 1, blade 1 would be the first sampled, port 2 would sample blade 5 and so on. This approach only works if the blade spacing and port spacing could always be assured to be nonredundant. Note what could happen if blade 5 were deflected ahead of its usual position. It would already have passed port 2 and thus the first blade sampled would be blade 6; however, it would be identified as blade 5 and the data validity would be ruined.

To overcome this difficulty, it was decided to insure that all ports started to take data at blade 1. If the rotational speed is known, a time can be calculated for the transit of blade 1 to any given position from some reference position. This time is stored in each port microprocessor. At the start of the experiment, all ports do not immediately start taking data. A 1/rev. signal is generated by the shaft transducer, and is sent to each microprocessor. This signal then starts a counter clocked at the microprocessor clock rate or some lesser rate generated by passing the clock through a divider. The angle clock pulse train could also be used and a somewhat arbitrary choice of time was made with the only advantage being that different measurement resolutions change the angle clock rate but not the microprocessor clock rate. The microprocessor is enabled and will accept the next blade arrival pulse as the number 1 blade after the preset count is reached. For example, if the rotor of fig. 6 is rotating at 1 885 rad/s and its position is as shown at the instant the 1/rev. signal is received, then typical times stored at each port could be as follows:

(Assuming that each microprocessor is enabled when blade number 1 is 20° away from the port).

Port	Angle of Rotation ($^{\circ}$)	Time Delay (μS)
1	10	93
2	100	925
3	190	1 759
4	280	2 593

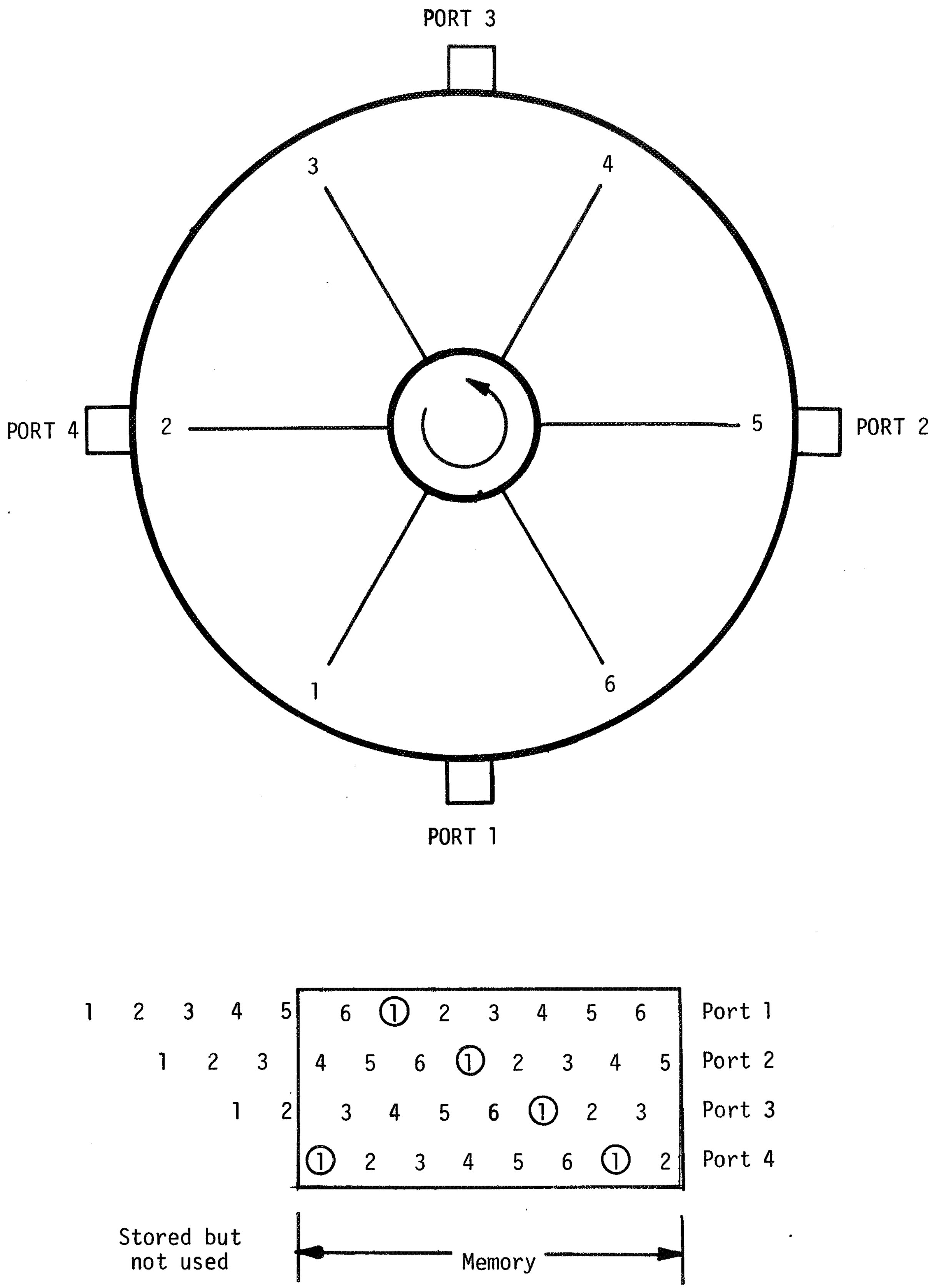


Fig. 6 . Hypothetical Six Bladed Rotor

Also if blade 1 were very close to port 1 at the time of the 1/rev signal, a possible error could result. Blade 2 could then be reidentified as blade 1 by simply adding 540 μsec to the delay time at each port in order to remove the possible error. Once the timer times out, the port will accept all signals as blade arrival pulses.

The method of taking data would produce the type of data storage at each port as shown at the bottom of fig. 6. It is desired that the data used as a data sample be time synchronous at all ports. When the data is transferred from the microprocessor to the CPU, the leading samples from the first revolution are neglected. Likewise, the trailing samples at the last port are neglected at the end of a test. This method of insuring proper blade identification results in two modifications to the experiment or the system design. In order to store number of deflection samples for a blade (which are in powers of 2 so that the Fast Fourier Transform can be performed), the storage capability at each port must be greater than 4 096 by the number of blades. Additionally, 65 revolutions will now be required instead of 64 revolutions for a 64-blade rotor.

Further, programming is simplified when each port starts to take data at the same blade. The simplification is very apparent when skipping blades. For example, if a rotor had 29 blades and it was desired to skip every other blade, the blades sampled would be 1, 3, 5 . . . 27, 29. After the 29th blade, the system must be programmed not to skip a blade and thus take data from blade 1 again. Each port can operate from the same set of commands.

Starting to take data at blade 1 will insure positive identification of all blade data as long as all the blade arrival signals are received. One problem could occur if a blade at a given port did not produce a reflected light signal large enough to be received. All subsequent blade identifications at that port would be out of sequence and the overall data from the test would be erroneous. Likewise, if a noise pulse were to be generated either from a reflection from foreign material passing through the engine or simply spurious electrical noise, all subsequent data would also be out of sequence. In using the measurement system with the test rig at NASA, the presence of this type of error is much less likely than when using the system with a real engine. Engineers at NASA, experienced in making this type of measurement on a real engine placed a high priority on the development of some method to allow the system to correctly identify the blade sequence following an extra or missing pulse.

An approach has been developed that will provide good protection against erroneous data with a reasonable increase in system complexity. The concept used is an expansion of the arm delay counter at each port that identifies the first blade. The concept establishes a time window (or more accurately, an angular window) at each port.

One and only one blade pulse will be accepted during this time. If no blade arrival pulse has been received at the end of the window time, an artificial "pulse" is generated so that a missing "blade" will not degrade subsequent data. Time cannot be used to set the window since it will not accommodate a drift in rpm. Counters available have a maximum rate of 2 mHz so that the ≃ 25 mHz angle clock must be divided by up to 16 so as not to exceed this rate. Problems with window drift occur if each of the ports are set to a constant and integral window count. To overcome these problems, an approach utilizing three counters was developed.

To understand the operation, the following signal and counter names are adopted.

BA	Blade Arrival Pulse -- could be valid, noise or nonexistent.
WCC	Window Closed Counter. BA is not accepted during WCC valid except in one special case.
WOC2	Window Open Counter -- Set to be equal roughly to possible angle blade can be expected.
WOC1	Counter set to twice the count of WOC2.
ABA	Signal accepted by system as blade arrival.

If the case of maximum resolution is examined where the angle clock must be divided by 16, then the following counter settings can be made.

$$\text{WOC2} = \frac{256}{16} + 2 = 18$$

(the 2 is a safety factor)

$$\text{WOCL} = 2 \times \text{WOC2} + \Delta$$

(Δ will allow window to drift in one direction)

$$WCC = \frac{C_A}{16\ N} + 1 - WOC2$$

$$= \frac{288 \times 256}{16 \times 64} + 1 - 18$$

(C_A is angle clock, N = # of blades)

Note that the sum of WCC and WOC2 is almost equal to the number of counts between blade arrival pulses. The almost plus the use of WOC1 are keys to resynchronizing the system to the blade arrival after serious upsets such as noise or missing blades.

The following definitions are used.

BA starts or restarts WCC and generates ABA if and only if

1) WOC1 is valid.
2) A previous BA has not occurred during current WOC1 valid cycle.

WOC2 is started only by WCC counter after it counts out. When WOC2 counts out, it starts WCC counter if WCC not valid (e.g., has not already been started by BA signal).

WOC1 is started only by WCC after it counts out. WOC1 must be valid for BA to generate ABA. When WOC1 counts out it generates ABA if BA has not generated ABA during current WOC1 cycle.

WCC is started or restarted by BA if it occurs during WOC1 valid cycle or is started by WOC2 counting out if BA has not occurred during current WOC1 cycle.

WOC1
WOC2 are started by WCC counting out.

Fig. 7 shows both cases where the blade pulse is missing and extra pulses (noise) arrive. Note the ability of the "window" to drift back in both directions to its proper place after a serious upset.

System Description

The turbojet blade vibration data acquisition and display system will include two subsystems: the control and display subsystem, and the data acquisition subsystem. The control and display subsystem will include the following units.

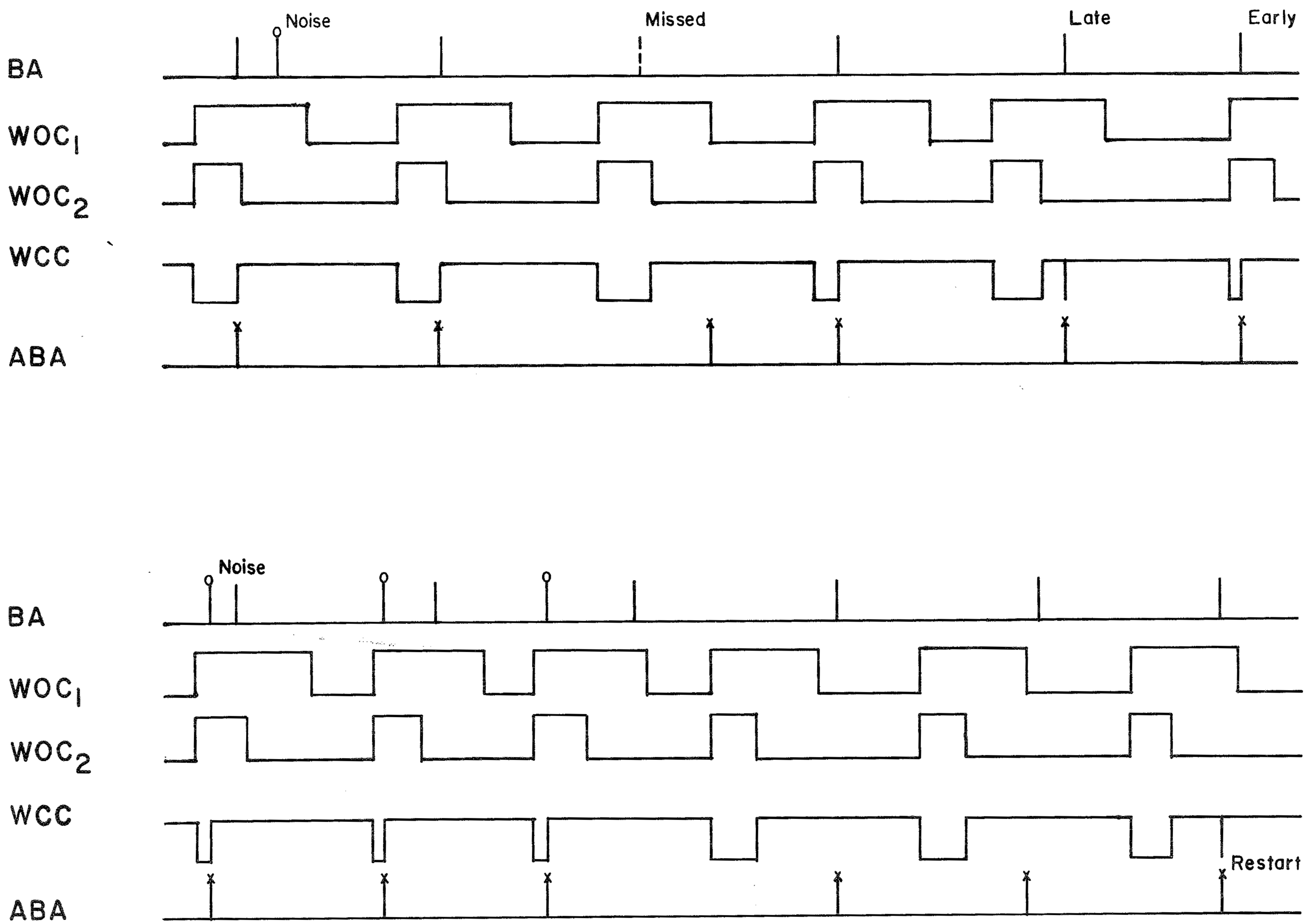


Fig. 7 Operation of Window Counters -- Showing Pulses Generated and Extra Pulses Rejected

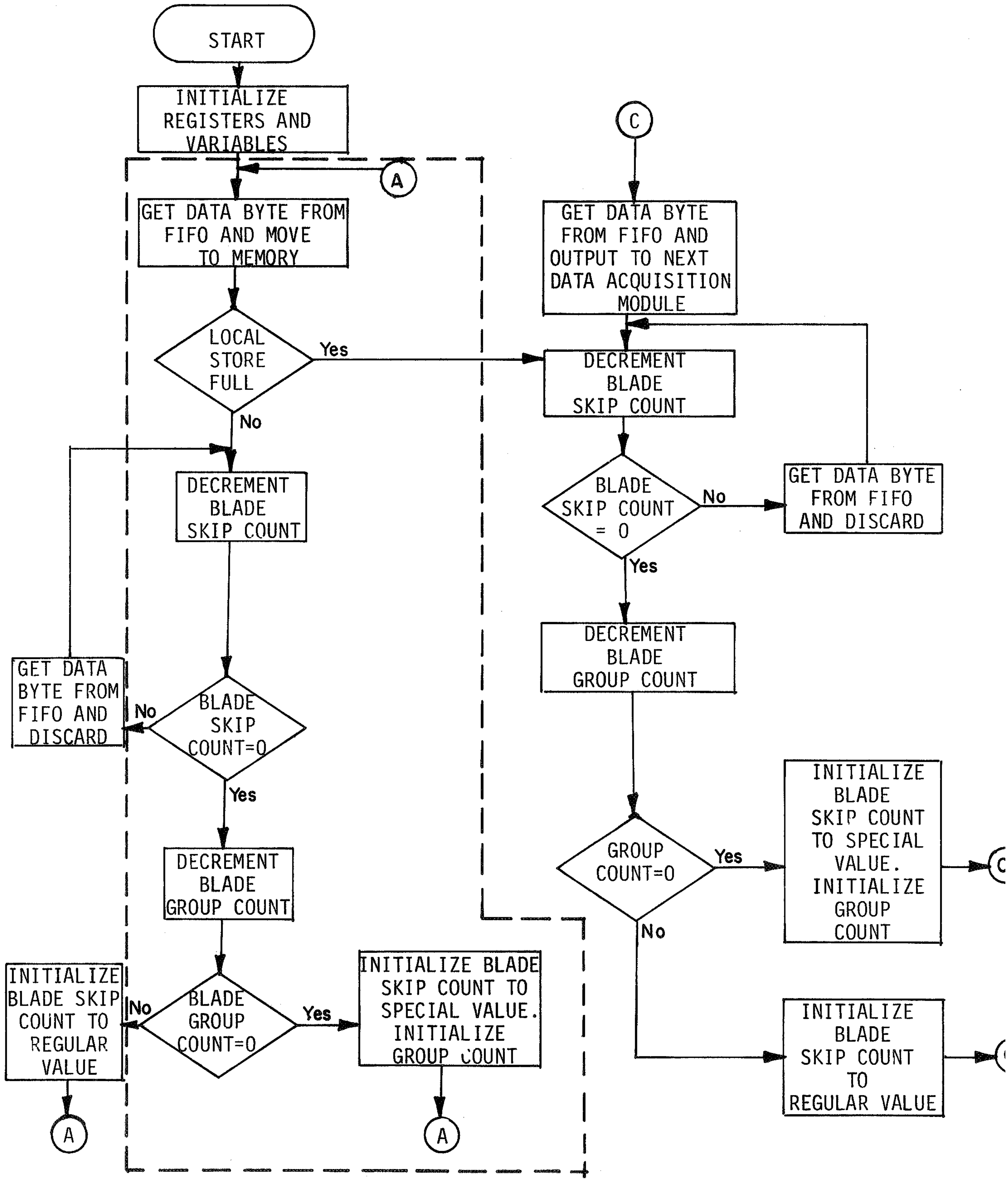
1. Hewlett-Packard 21 MX Computer
2. Hewlett-Packard 7900 Disk Memory
3. Keyboard CRT Terminal for Control
4. Angle Clock Generator
5. Graphics Terminal (may be the same as 3)
6. Interface to Hewlett-Packard 2100S Computer

The data acquisition subsystem will consist of a microprocessor controlled data acquisition module for each of three probes at each of 32 ports. The data acquisition modules will all be connected to a control bus and a data bus through which they will communicate with the computer in the control and display subsystem. The data acquisition modules also receive the eight least significant bits of the digital shaft angle as output by the angle clock generator as a result of counting angle clock pulses.

The data acquisition modules each receive an ARM signal which originates with the 1/rev. signal in the control and display subsystem. This signal is used to synchronize the start of data acquisition by the data acquisition modules so that the first data point stored by each module is from the first blade. The data acquisition modules are also daisy chained by an 8-bit path (plus necessary control lines) for passing data for storage when only 1/2, 1/4, or 1/8 of the ports are being used in order to increase the number of data points taken at each sample point. Each port has three probes and each probe has an associated data acquisition module which can be designated A, B, and C. The daisy chaining connects A data acquisition modules at adjacent ports to each other and likewise for the B and C data acquisition modules. The three data acquisition modules at any one port are not connected to each other.

Microprocessor Selection. Several candidate microprocessors were reviewed. These were the Zilog Z80 and S80A. the Intel 8085 and the Motorola 6800. In order to select the appropriate processor, the system was analyzed and the critical timing operation was identified. This turned out to be the operation of the microprocessor when it is taking data at the maximum rate with the possibility of either skipping blades or passing data on to the next module. This operation was flow charted as shown in fig. 8. The critical loop was identified and this loop was coded using the manufacturers' assembly instructions. Also using manufacturer data, the time for each coded step was summed to obtain the total time for the critical loop. These times are given below:

DATA ACQUISITION MODULE TAKE DATA FROM PROBE COMMAND



Note: Dashed Line Outlines Critical Loop

Fig. 8 Data Acquisition Module Take Data From Probe Command

Microprocessor	Time to Execute Critical Loop
Z80	47.15 μS
Z80A	28.75 μS
6800	59 μS
8085	45.21 μS

At the maximum rotor speed of 1 885 rad/s and using 64 blades on the test rotor, the time between blade arrival pulses would be 52 μS. On the face of it then, it would seem that three of the four processors would be capable of performing the operation in the required time. If, however, blade deflection is taken into account, even the fastest processor may not be fast enough to handle the case where two successive blades have large deflections in opposite directions so that the time between their arrivals at a given port could be very small.

To overcome this situation, a FIFO (First In, First Out) buffer was added so that only the average time of 52 μS need be a consideration. As a result of the critical loop timing, the addition of the FIFO and the fact that a fall back position to the Z80A would be possible by simply a chip replacement, the Z80 was chosen as the microprocessor.

Overall System Block Diagram. Fig. 9 shows the overall system block diagram with emphasis placed on the resulting bus structure. The data acquisition modules (DAM) are grouped into three groups of 32 each and each group labelled as A, B or C after the three probes at a given port. The control board is split into two sections labelled the TTL (Transistor-Transistor Logic) control board and the ECL (Emitter Coupled Logic) control board.

The computer talks only to the TTL portion of the control board and to outside peripherals such as the graphic terminal. The maximum angle clock rate is close to 25 mHz and therefore the transmission of an 8 bit data plus valid pulse from a counter to all 96 DAM's was considered marginal if TTL circuitry was used. For this reason, ECL circuitry was selected for the angle clock counter (located on the ECL control board) and the interface between the count bus and the individual DAM's. The count bus is split into three sections. Each section connects the ECL control board to one group of 32 DAM's. The control bus and the data bus connect the TTL control board to each of the 96 DAM's. The control bus is used to send instructions to the DAM's while the data bus is used to extract data from the DAM's. Likewise, the TTL control board talks to the Hewlett-Packard computer via its data bus and listens to the computer via its control bus.

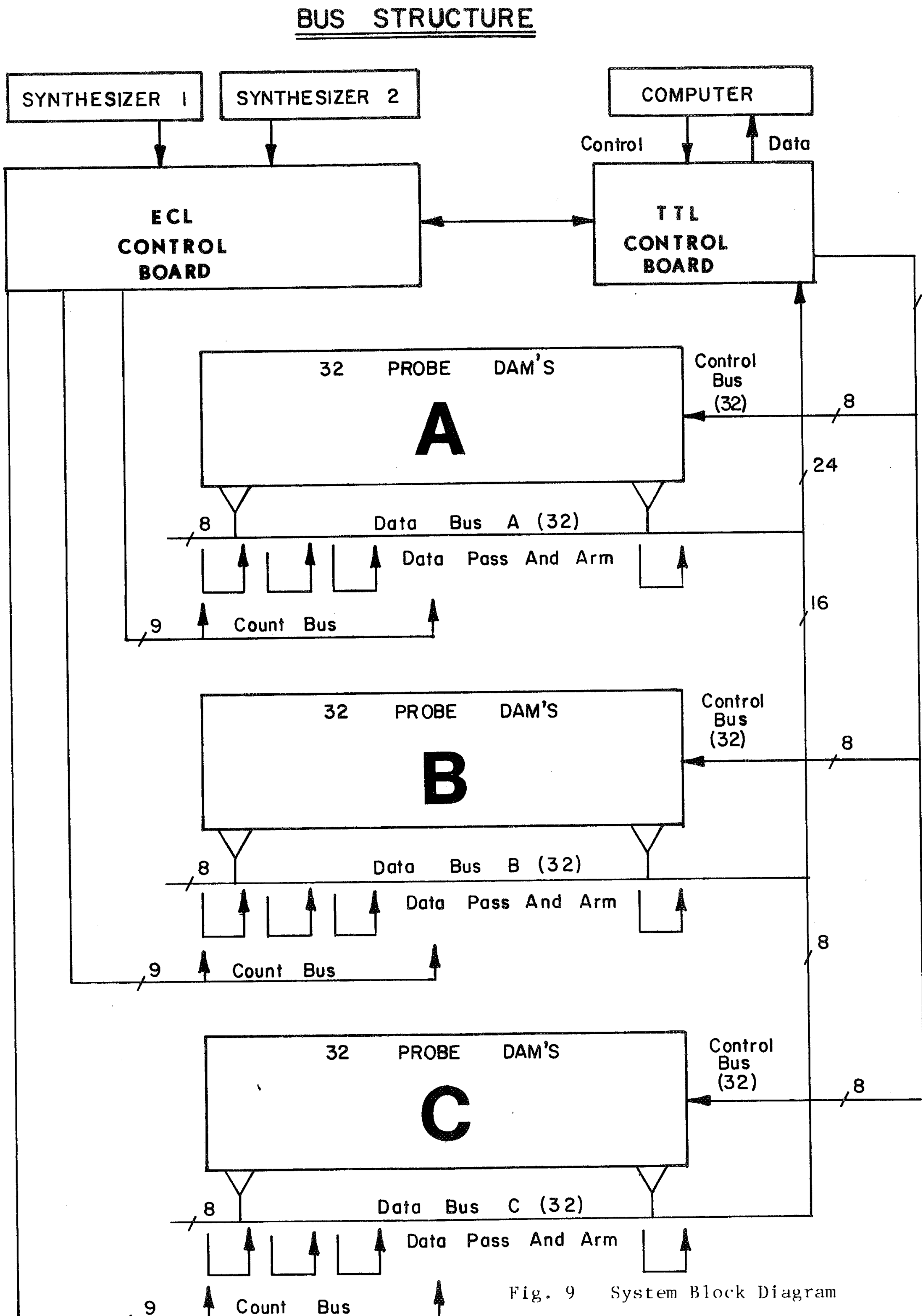


Fig. 9 System Block Diagram

Data pass and arm buses interconnect all of the processors on a given level in daisy chain fashion.

With this overall system structure, the hardware can be completely described by a discussion of the DAM board and the two control boards. The software can be described by a discussion of the microprocessor software and the control computer software.

DATA ACQUISITION MODULES (DAM)

All of the 96 data acquisition modules which comprise the data acquisition subsystem are identical. The block diagram for the DAM is shown in fig. 10. Each DAM includes a Zilog Z80 Processor, a 4k x 8-bit Dynamic RAM, a 256 x 8-bit Static RAM and a 1024 x 8 bit Prom. There are six 8-bit plus control line input/output ports and four programmable counters. The rest of the board is made up of the blade detect logic, the FIFO and ECL count bus interface.

The program for the Z80 operation is located in the PROM. The I/O ports are assigned as follows:

1. Data to data bus -- Is used to transmit data from the DAM to the control board and then to the computer.
2. Board location tag -- Each DAM mating connector is wired with a 7-bit tag so the board knows where it is located and so that it may respond to the proper commands.
3. Data to next module -- Each DAM is instructed to store a given amount of data after which the data is sent to this output port.
4. Data from previous module -- Data from the previous module is received at this input.
5. Commands from control board -- This is the input port for the receipt of control board commands. Note commands to all processors are common to this input port. The processor will only act on those addressed to it.
6. Status bus -- This is actually the handshake arrangement for the control bus.
7. Count bus -- The angle clock count after the blade detect pulse is received is picked up at this point.

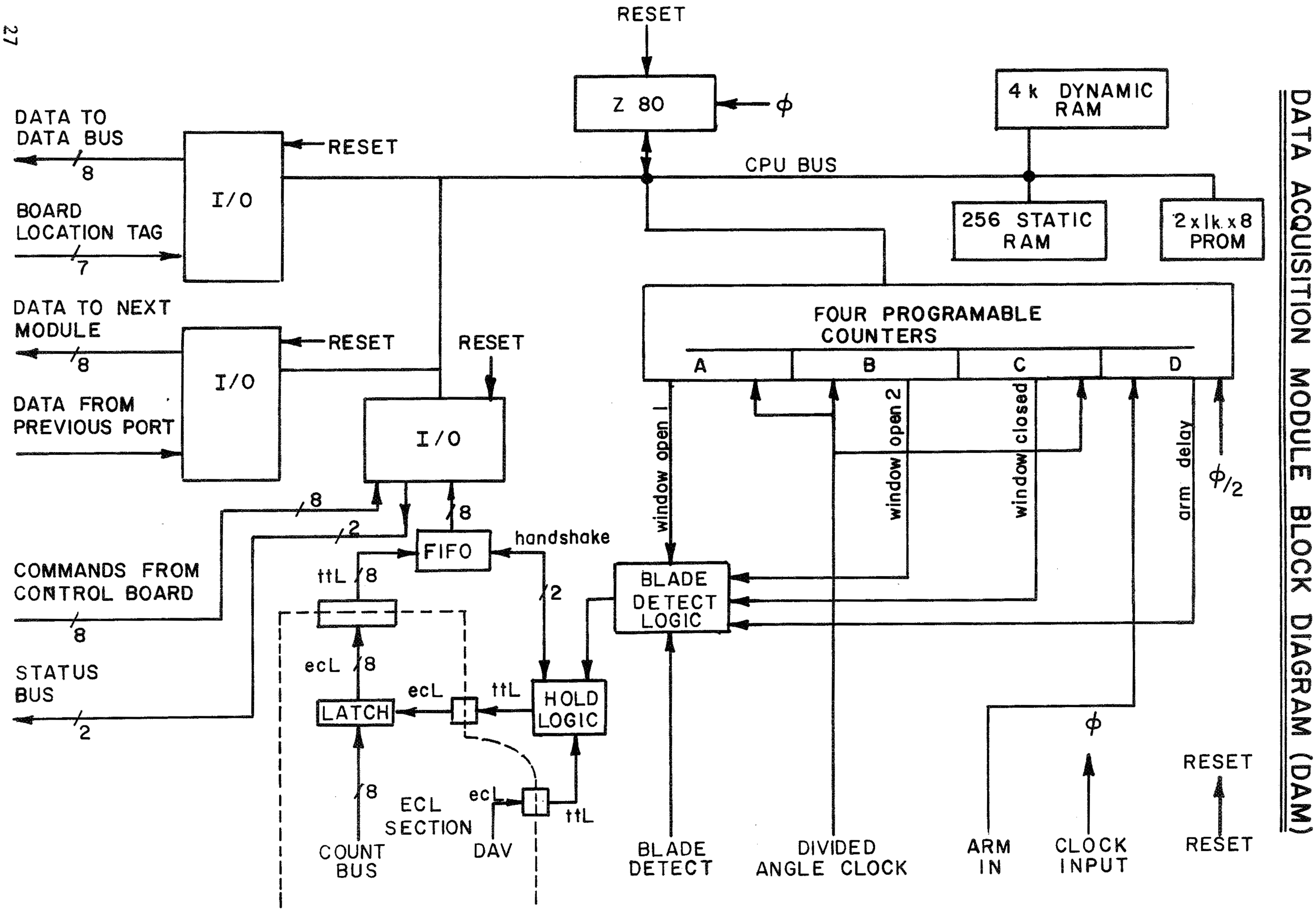


Fig. 10 DAM Block Diagram

The divided angle clock pulse train is the input to the window closed counter (WCC), the window open counter 1 (WOC1) and the window open counter 2 (WOC2). The microprocessor clock divided by 2 (Ø/2) is the input to the arm counter. The output of all four counters, plus the blade detect pulse are input to the blade detect logic. The operation of this logic was previously described. When a valid blade arrival pulse is received, the latch is programmed to latch the next valid count. A handshake arrangement exists between the Hold Logic and the FIFO to insure that valid counts are accepted by the FIFO. The dotted line separates the ECL interface from the balance of the DAM which is TTL.

CONTROL CARD

The block diagram for the control card is shown in fig. 11.

The Hewlett-Packard computer interfaces to the measurement system through a microcircuit interface card. This card provides for 16-bit output and input on separate lines. These two 16-bit buses generate inputs to, and accept output from the control buses (A, B, and C), the count buses (A, B, and C), the data buses (A, B, and C), the status bus, the synthesizer control, the divided angle clock, the arm out signals from the first board in A, B, and C and the one per rev pulse train from the test rig.

It is simplest to start the discussion of the control card with the 16-bit bus that sends data to the computer. This data bus is connected to one of four 16-bit buses through the one of four multiplexers. Two of these data buses are used to transfer data from the Data Acquisition Modules to the computer and two are used to send angle clock information to the computer. There are three 8-bit data buses coming from the three groups of Data Acquisition Modules. In addition to these data buses, there are six lines which tell the status of the Data Acquisition Modules; independent data ready for each bus, any one module ready, all modules ready and all three bus' data ready (latter is actually formed on the control board from the three data ready signals). The data ready lines are associated with receiving data from the DAM. The one ready and all ready are associated with the receipt by the DAM of control bus commands. The one ready and all ready are used in combination as a diagnostic tool to insure all 96 microprocessors are responding.

The three 8-bit buses and the 6-bit status bus are grouped as shown in the block diagram. This means that when data is being transferred from the B or C bus, the multiplexer must switch back and forth to observe the status bus.

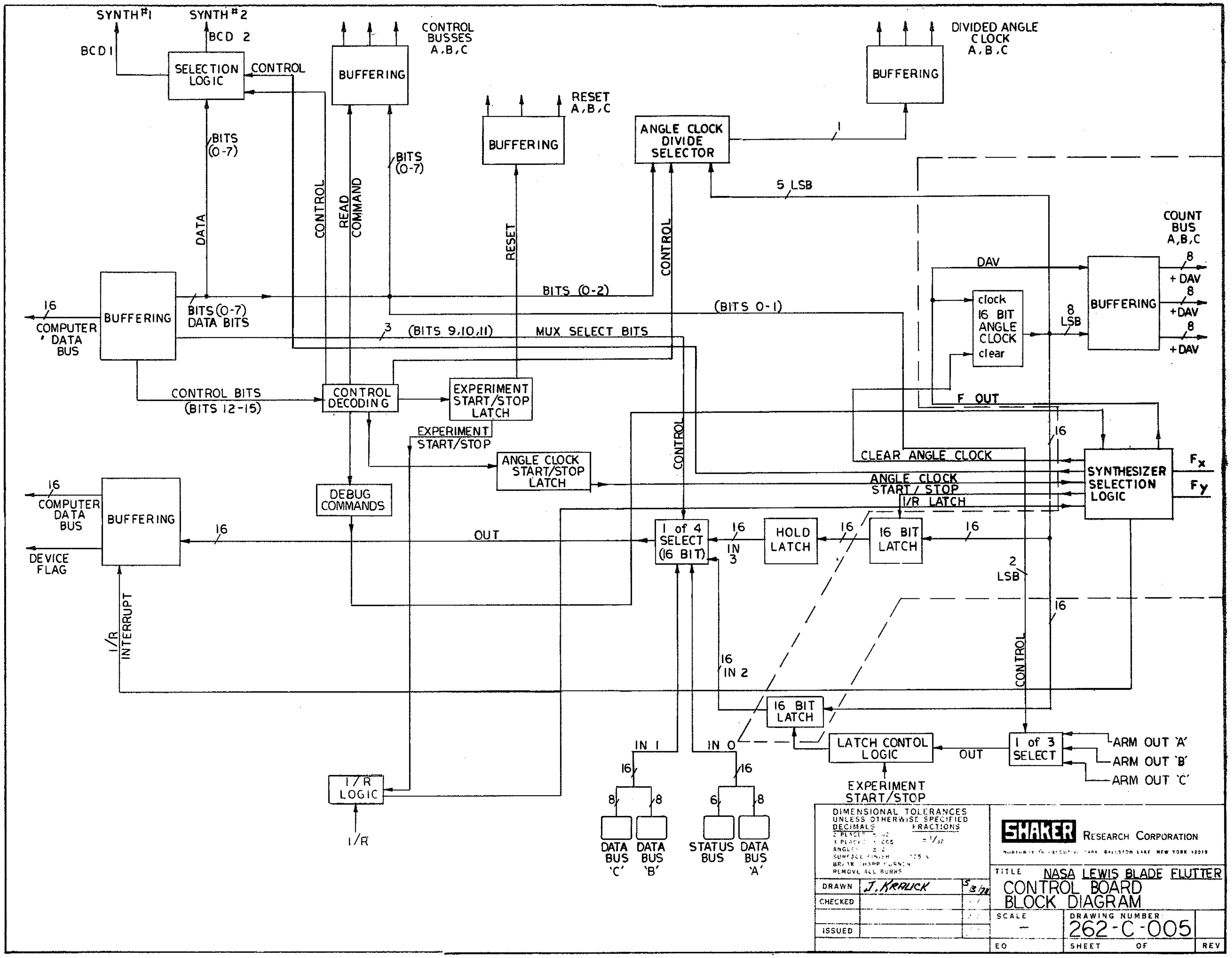


Fig. 11 Control Board Block Diagram

The two 16-bit words that are associated with the angle clock are stored in the two 16-bit latches. One is latched by the arrival of the 1/rev. pulse generated by the test rig. This is the count of the angle clock for one revolution. It is sent to the computer where it is compared to the desired count and the synthesizer command is updated. The computer is informed that this word is ready by an interrupt generated on the device flag line of the control computer microcircuit interface card. The second 16-bit word is the angle clock count when the first blade arrives at the first port. It is latched by one of the three microprocessors tending this first port. This information is used by the computer to insure that the first blade arrival at port 1 is long enough after the 1/rev. so that no ambiguities occur if this blade is vibrating.

The function of the four 16-bit buses are as follows. The bus giving the count to the first blade arrival at port 1 is used only during the experiment setup. The data buses (A, B, and C) are selected only for transfer of data to the computer after the experiment. The status bus is queried at this time as well as when commands are being sent to the DAM's. No commands are sent during data acquisition. Therefore, the only 16-bit line that is active during data acquisition is the one that contains the angle count per revolution.

The 16-bit bus from the computer to the control board carries the command information. The 9 least significant bits (LSB) 0-8 are used to provide data to the synthesizer, the DAM's and the angle clock selector. The synthesizer is the only device that expects a 9-bit data input with the others much less. The next three bits -- 9, 10 and 11 -- are used to select one of four lines at the mux. Bits 12-15 contain the read command codes. The codes (in hex) are shown in Table II.

For example, if it is desired to use Command Code 5 to tell the control board to divide the angle clock by 16 then the following code would be generated:

0101	0000	0000	0100	(Binary)
5	0	0	4	(Hex)

The 5 is the command code, 0 selects the status and DAM A position while the 0 4 means that the angle clock should be divided by 2^4 or 16.

A reset is sent to all DAM's on the experiment Stop Command. The clear angle clock command is not sent from the computer, but is generated by Synthesizer Selection logic automatically at the time the switch is made. The only active command lines during the experiment are those sending the synthesizer frequency select commands.

TABLE II

COMMAND CODES

Code	Mnemonic	Command	Data
0	CBO	Control Bus Output	8 bits data desired sent
1	ESTOP	Experiment Stop	No data
2	ESTART	Experiment Start	2 bits (which sensor at port 1 latches the counter)
3	LBCL	Synthesizer 9 MSB	9 bits } preliminary depends on actual synthesizer chosen
4	LBC2	Synthesizer 9 LSB	9 bits
5	ACS	Angle Clock Divide	3 bits (0-4 is power of 2 for division)
6	Spare	---	---
7	Spare	---	---
8	CAC	Clear Angle Clock	No data
9	SAI	Simulated Arm In	No data
A	INAC	Increment Angle	No data
B	ASTOP	Angle Clock Stop	No data
C	ASTART	Angle Clock Start	No data
D	Spare	---	---
E	Spare	---	---
F	Null	NOP	No data

The mux commands are as follows:

0	Status and A Data	2	Content of Latch 1
1	B and C Data	3	Content of Latch 2

A few other items need to be noted for clarification of the block diagram. The angle clock divide selector is used to generate a train of pulses to determine shaft angle with four different resolutions. This pulse train is counted at each DAM and is used to establish a window for the blade arrival pulse. During the window, only one blade arrival pulse is accepted and if none have occurred by the end of the window, an artificial pulse count is generated.

DATA ACQUISITION MODULE SYSTEM SOFTWARE

The next step in understanding the operations of the system is to examine the commands that are accepted by the Data Acquisition Module. These commands along with the previous concept and DAM hardware discussion will clarify the DAM and system operation. Table III is the list of commands accepted by the DAM. The command code is given in hex code. The command name and the DATA BYTE (S) expected by the system are included. When the microprocessor is reset by a signal from the control computer or when it completes execution of a command, it will monitor the system control bus for commands and interpret each one. Commands addressed either to its port or to all data acquisition modules will be executed. The following is a description of each command.

Set Regular Skip Count (01). The Set Regular Skip Count command causes each data acquisition module to read and store the Regular Skip Count from the control bus. This is the number of blades to be ignored after each blade for which data is taken, except after the last blade in a revolution.

Set Special Skip Count (02). The Set Special Skip Count command causes each data acquisition module to read and store the Special Skip Count from the control bus. This is the number of blades to be ignored after the last blade in each revolution for which data is taken.

Set Group Count (03). The Set Group Count command causes each each data acquisition module to read and store the Group Count from the control bus. This is the number of blades for which data will be taken on each revolution.

Set ARM Delay (04). The Set ARM Delay command causes each addressed data acquisition module to read and store the ARM delay time from the system control bus. This value is used to initialize the delay circuit in the special interface circuitry each time data acquisition is about to begin. The subsequent data words set the window closed counter and the two window open counters.

TABLE III

LIST OF COMMANDS ACCEPTED BY DATA ACQUISITION MODULE

COMMAND CODE (HEX)	COMMAND	DATA BYTE(S)
01	Set Regular Skip Count	Skip Count
02	Set Special Skip Count	Skip Count
03	Set Group Count	Group Count
04	Set ARM Delay	Module Address, Delay Time MSB, Delay Time LSB, Window Closed MSB, Window Closed LSB, Window Open 1 MSB, Window Open 1 LSB, Window Open 2 MSB, Window Open 2 LSB
05	Set Local Store Count	-Number Revs MSB,-Number Revs LSB
06	Take Data from Probe	Port Address
07	Take Data from Previous Module	Port Address
08	Calculate Expected Values	None
09	Accept Expected Values from Previous Module	Port Address
0A	Send Expected Values to Next Module	Port Address
0B	Set Expected Value Table	Module Address, Number Bytes, Data Bytes
0C	Calculate Deflections	None
0D	Provide First Expected Value	(First Port Responds)
0E	Provide Next Expected Value	(Each Port Responds in Turn)
0F	Provide Maximum Deflection	Port Address
10	Provide First Max Value for Blade	Blade Number (First Port Responds)
11	Provide Next Max Value for Blade	(Each Port Responds in Turn)

TABLE III (cont.)

COMMAND CODE (HEX)	COMMAND	DATA BYTE(S)
12	Enable Ports to Transmit Values	Number of Ports, Port Addresses
13	Provide First Value for Blade	Blade Number (First Enables Port Responds)
14	Provide Value for Blade	(Each Enabled Port Responds in Turn)
15	Provide Contents of Memory	Port Address, Memory Address MSB, Memory Address LSB
16	Provide Contents of Next Memory Location	None
17	Store into Memory	Module Address, Memory Address MSB, Memory Address LSB, Data Words (Terminated with Reset)
18	Jump to Command	Module Address, Memory Address MSB, Memory Address LSB
- - - - - -	- - - - - - - - - -	- - - - - - - - - -
19	Output to Control Board	8 Most Significant Bits, 8 Least Significant Bits
40	Include File	File Name in ASCII (Must be Last on a Line)

MSB Most Significant Byte

LSB Least Significant Byte

The commands below the dotted line are commands to the development system and are included in this table for convenience since they were used along with DAM commands in the feasibility testing.

Set Local Store Count (05). The Set Local Store Count command causes each data acquisition module to read and store the Local Store Count from the control bus. This is the number of revolutions for which data is to be stored in each data acquisition module.

Take Data from Probe (06). The Take Blade Data from Probe command is addressed to the three data acquisition modules at a a specific port. The data acquisition modules will initialize their special interface circuitry and their internal storage and then start a program loop to take and store data in the 4K byte data memory. After a data word is accepted from the special interface circuitry and store, the program will ignore the next N data words where N is the number of blades to be skipped. When the data memory is full, the program will output the data to the next data acquisition module instead of trying to store it in the data memory. The program loop will run until the microprocessor program is restarted by a rest signal.

Take Blade Data from Previous Module (07). The Take Blade Data from Previous Module command is addressed to the three data acquisition modules at a specific port. The data acquisition modules will initialize their special interface circuitry and their internal storage and then start a program loop to take data from the previous data acquisition module and store it in the 4K byte data memory. When the data memory is full, the program will output the data to the next data acquisition module instead of trying to store it in the data memory. The program loop will run until the microprocessor program is restarted by a rest signal.

Calculate Expected Values (08). The Calculate Expected Values command will cause each data acquisition module to average samples from each blade. The results will be stored in an Expected Value Table in the RAM scratchpad memory.

Accept Expected Values from Previous Module (09). The Accept Expected Values from Previous Module command is addressed to the three data acquisition modules at a specific port. Each of the three modules will accept data from its previous module which is passed along the daisy-chain bus and store it in its Expected Value Table. This command allows expected values to be passed to an inactive module. In this manner, each module will use the proper expected values when data is passed to an inactive port from an activated port.

Send Expected Values to Next Module (0A). The Send Expected Values to Next Module command is addressed to the three data acquisition modules at a specific port. Each of the three modules will send the contents of its expected value table along the daisy chain to the next module one word at a time.

Set Expected Value Table (0B). The Set Expected Value Table command causes the addressed data acquisition module to read the values for its Expected Value Table from the control bus. This is used to renew the expected value table from the control computer.

Calculate Deflections (0C). The Calculate Deflections command will cause each data acquisition module to transform the raw data in its 4K data memory into deflection data by subtracting the expected value for each data point from the actual value.

As the deflection values are calculated the highest deflection value (absolute value) for each blade is found and saved. When the operation is complete the largest of these values is found and saved.

Provide First Expected Value (0D). The Provide First Expected Value command causes the data acquisition module at port 1 to output the first value in their Expected Value Table onto their respective Data Buses.

Provide Next Expected Value (0E). The Provide Next Expected Value command causes the data acquisition modules at a port to output the next value from their expected value tables onto their respective data buses.

All the data acquisition modules reset some internal counters when the Provide First Expected Value command is received and increment them as Provide Next Expected Value commands are received. In this way each module keeps track of whose turn it is to respond.

Provide Maximum Deflection (0F). The Provide Maximum Deflection command causes the data acquisition modules at the addressed port to output the maximum deflection value in their data memories to their respective data buses.

Provide First Maximum Value for Blade (10). The Provide First Maximum Value for Blade command causes each data acquisition module to store the blade number and causes the port 1 data acquisition modules to output the maximum deflection value for the indicated blade. This starts the process that allows a quick look at data following an experiment.

Provide Next Maximum Value for Blade (11). The Provide Next Maximum Value for Blade command causes the data acquisition modules at the next port in turn to output the maximum deflection value for the blade set in the previous Provide First Maximum Value for Blade command.

Enable Ports to Transmit Values (12). The Enable Ports to Transmit Values command causes each data acquisition module to save the port numbers of the enabled ports for use with the next two commands.

Provide First Value for Blade (13). The Provide First Value for Blade command causes the data acquisition modules at the lowest numbered port which is enabled to output the first deflection value for the indicated blade. All the data acquisition modules save the blade number and initialize a pointer to the first value for the blade in their memories.

Provide Next Value for Blade (14). The Provide Next Value for Blade command causes the data acquisition modules at the next enabled port in turn to output their next deflection values for the blade indicated in the last Provide First Value for Blade command.

Provide Contents of Memory Location (15). The Provide Contents of Memory Location command causes all the data acquisition modules to store the port address. The data acquisition modules at the indicated port save the address, read and output the contents of that address to the data bus, and increment the address.

Provide Contents of Next Memory Location (16). The Provide Contents of Next Memory Location command causes the data acquisition modules at the port addressed by the last Provide Contents of Memory Location command to read and output the contents of the stored memory address and then increment the address.

Store Into Memory (17). The Store Into Memory command causes the addressed data acquisition module to store successive bytes of data from the control bus into its memory starting at the indicated address until the microprocessors are reset. If the module address is set to 255 (all binary ones), all the data acquisition modules perform the storage operation in parallel.

Jump To (18). The Jump To command causes the program in the module addressed to jump to a new memory address. The following two commands are not accepted by the DAM's, they are utilized by the central processor to facilitate conducting experiments and are listed here for convenience only.

Output to Control Board (19). The Output to Control Board causes the development system to output a string of bits to the control board. This command could be used to implement any of the above commands or those commands of Table II.

Include a File (40). The Include a File command allows the development system to store a series of the above commands and on command output these commands one at a time. This is simply a convenient way to output a series of commands rather than typing each command in one at a time.

The use of the commands in conjunction with the breadboard system for feasibility testing is discussed in a later section.

CONTROL COMPUTER

The operator will enter commands at the keyboard CRT terminal to control operation of the system. The operator will have the following set of commands to control data acquisition.

1. Specify Number of Blades
2. Specify Number of Sample Ports
3. Specify Number of Blades to Skip
4. Specify Number of Data Points Desired per Probe
5. Specify Deflection Resolution
6. Start Normalization Run
7. Get Expected Values from a File
8. Start Presample Mode
9. Start Data Collection Run

10. Store Data in a Disk File
11. Display Data from a Disk File
12. Move Data to Fixed Format Disk
13. Send Data to 2100S

Specify Number of Blades. The Specify Number of Blades command will be used by the operator to enter the number of blades on the rotor under test. This command will be needed only when the system is powered up or the rotor is changed. The program will save the number of blades and output it to the data acquisition modules.

Specify Number of Sample Ports. A total of 32 sample ports will be included in the system; however, the operator will be able to use the Specify Number of Sample Ports command to specify a sub-multiple of the 32 ports for use in order to extend the effective data acquisition memory available to the active ports at the cost of a reduction in the effective sampling rate of blade deflections.

Specify Number of Blades to Skip. The Specify Number of Blades to Skip command will be used to specify the number of blade passings to be ignored at each port for each blade whose angle of deflection is recorded. The default value for this number will be zero so that data for all blades will be recorded. By specifying a higher number the operator can get more data points for each of the blades not skipped. Fewer blades may be skipped after the last blade for which data is taken so that data will be taken from the same blades in each revolution. The program will save the specified number and output it to the data acquisition modules.

Specify Number of Data Points Desired per Probe. The Specify Number of Data Points Desired per Blade command will be used by the operator to specify the number of data points to be stored and displayed for each probe for each blade. The maximum number which can be specified is

$$\frac{131\ 072}{\text{NBLADES X NPORTS}}$$

where NBLADES is the number of blades from which data is being taken and NPORTS is the number of ports in use. (131 072 = 64 x 64 x 32 so that if data is taken from all 64 blades and all 32 ports are active, then 64 data points per blade per port are saved.)

Specify Deflection Resolution. The Specify Deflection Resolution command will be used by the operator to specify the size of the smallest deflection which will be detectable by the system. The maximum amplitude of the deflection can be no greater than 127 times the smallest deflection since the system uses 8 bits to measure deflections and one of them is a sign bit.

The program will use the number entered to calculate the number of pulses to be generated by the angle clock generator during each shaft revolution.

Start Normalization Run (See Figure 12 for Flow Chart). The Start Normalization command first allows the operator to enter the file name where the expected values will be stored and then causes the program to perform the following operation.

a. Calculate the ARM delays and output them to the data acquisition modules.

b. Command the data acquisition modules to take blade data.

c. Initialize and start the angle clock generator.

d. Wait until the data acquisition modules have collected 4 096 bytes of data.

e. Reset the data acquisition modules.

f. Command the data acquisition modules to calculate expected values.

g. Move the expected values from the data acquisition modules to a work area on disk.

h. If data is to be taken from only a fraction of the ports, use the Accept Expected Values from Previous Module and Send Expected Values to Next Module commands to move the expected values to the data acquisition modules which will only be used for data storage.

This command must be used whenever the rotor under test is changed or the mechanical alignment of the test rig has been disturbed. In addition, this command or the Get Expected Values from a File command must be used after the Specify Deflection Resolution command has been used in order for the system to calculate valid deflection data in response to subsequent commands.

The command must be issued while the blades are not vibrating.

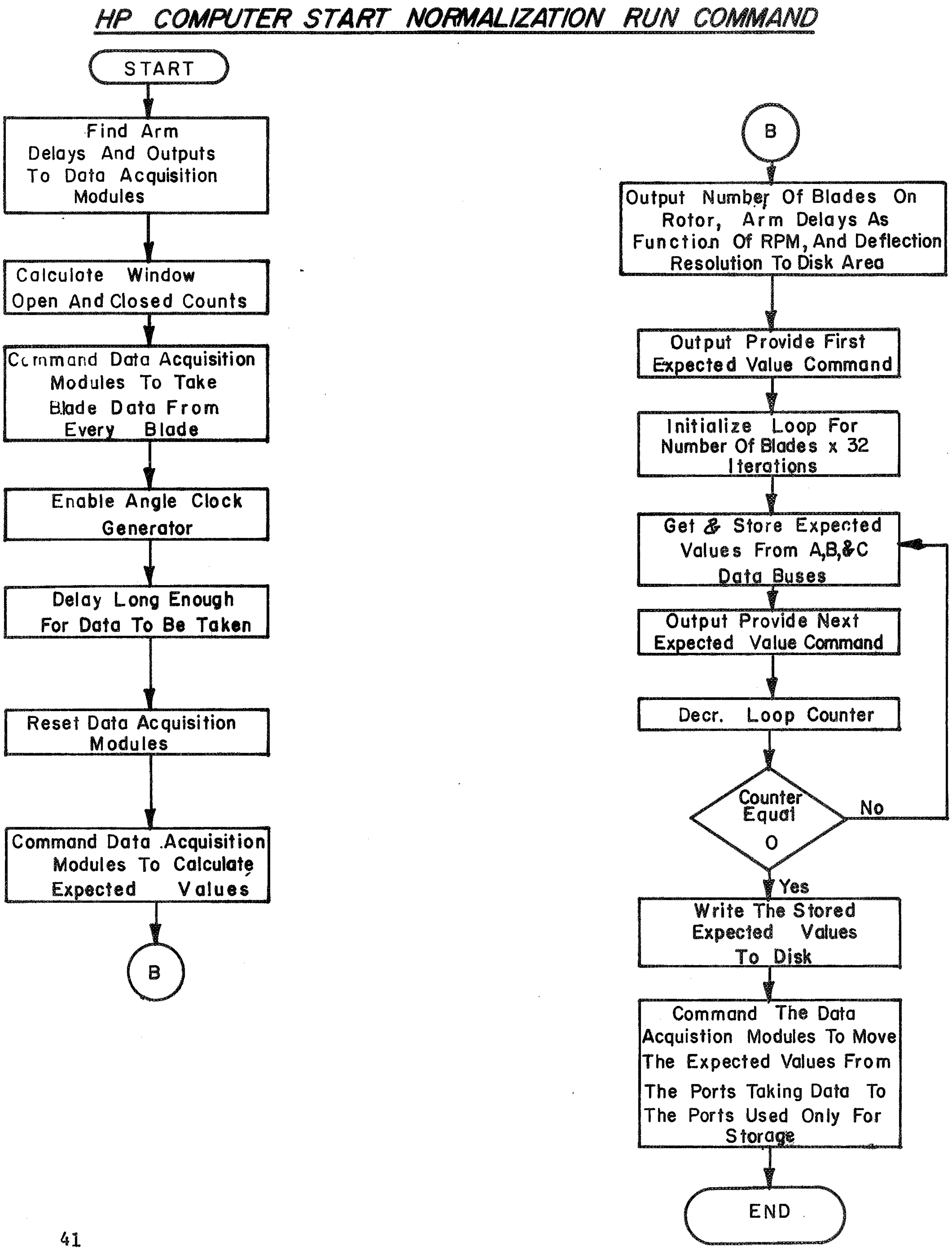


Fig. 12 HP Computer Start Normalization Run Command

Get Expected Values from a File. The Get Expected Values from a File command allows the operator to specify the name of a file where expected values for a given rotor and deflection resolution are stored. The values are moved to a work area on disk and to the data acquisition modules which are to take data. If data is to be taken from only a fraction of the ports, the data acquisition modules will be commanded to move the expected values to the modules which will only be used for data storage.

Start Presample Mode. The Start Presample Mode command will cause the program to perform the following operations in a continuous loop.

a. Command the data acquisition modules to take blade data.

b. Initialize and start the angle clock generator.

c. Wait until 4K works of data have been collected at each active port.

d. Reset the data acquisition modules.

e. Command the data acquisition modules to calculate deflections.

f. Get the maximum deflection and the maximum deflection for each blade from the active data acquisition modules.

g. Display the maximum deflection and the maximum deflection for each blade on the keyboard CRT terminal.

h. Get all the data from the first port and display it on the graphic display unit.

Start Data Collection Run (See Figure 13 for Flow Chart.) The Start Data Collection Run command will cause the program to perform the following operations.

a. Command the data acquisition modules to take blade data.

b. Initialize and start the angle clock generator.

c. Wait until the maximum amount of data which can be stored has been collected.

d. Reset the data acquisition modules.

e. Command the data acquisition modules to calculate deflections.

f. Get the maximum deflection and the maximum deflection for each blade from each data acquisition module.

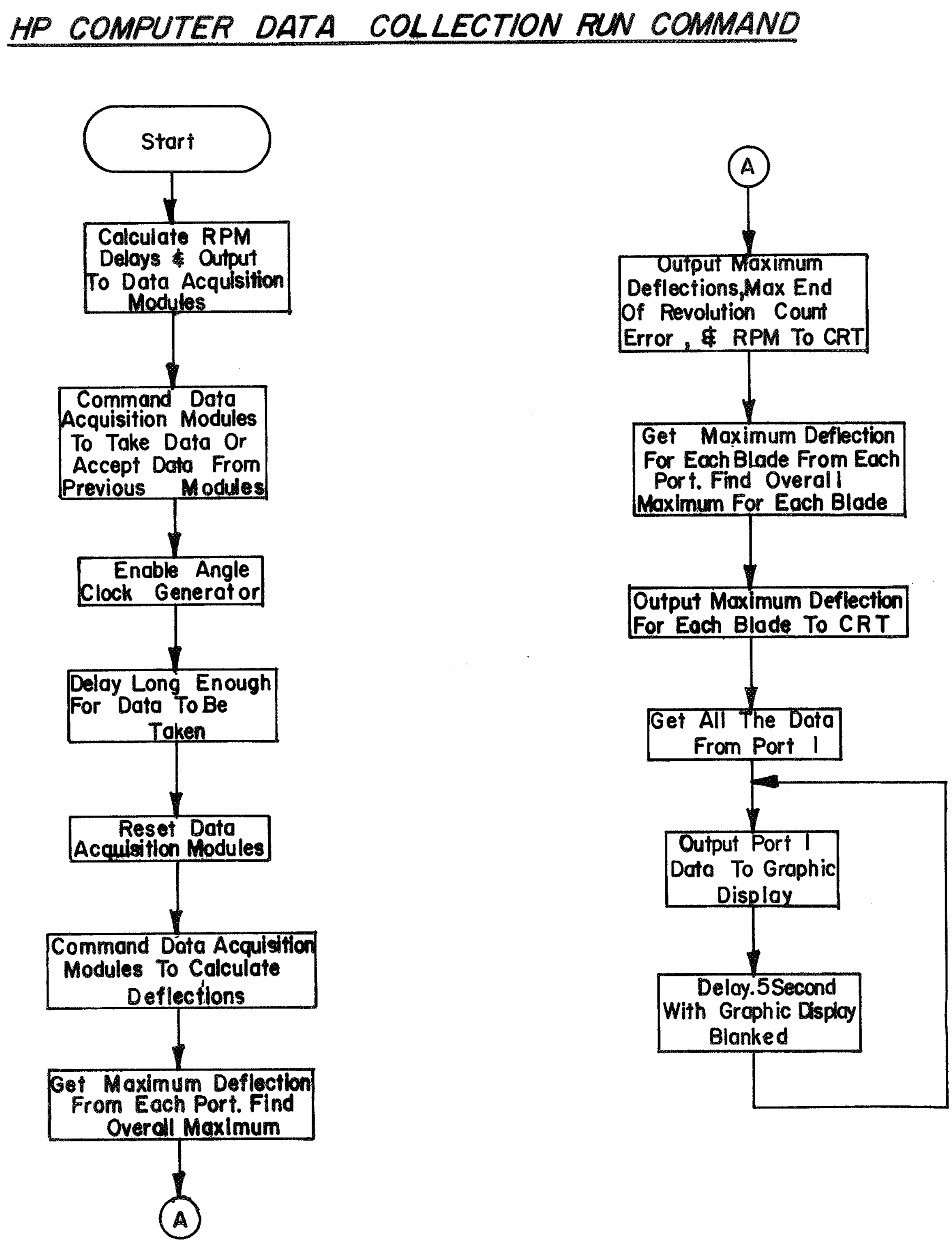


Fig. 13 HP Computer Data Collection Run Command

g. Display the maximum deflection and the maximum deflection for each blade on the keyboard CRT terminal.

h. Get all the data from the first port and display it on the oscilloscope display unit.

<u>Store Data in a Disk File (See Figure 14 for Flow Chart).</u> The Store Data in a Disk File command will cause the program to perform the following operations.

a. Get the file name from the operator and open the file.

b. Get identifying comments from the operator and store them in the file along with the constants entered with the first five commands and the rotor speed during data collection.

c. Get the blade data, in sequence by blade, from the data acquisition modules and store it in the file.

The data will be stored in an HP Type 1 File Manager file. The first 128 word block will contain the identifying information about the file. The next block and as many subsequent blocks as are necessary will contain the data for the first blade. The following set of blocks will contain the data for the next blades, etc. Each data block contains 85 sets of blade data with each set consisting of 3 bytes (A probe displacement, B probe displacement). The 255 data bytes are followed by a zero byte. The data for each blade begins in a new sector. Unused data bytes in the last sector for a blade are set to zero.

The identification block for the file will include the following information.

a. Date and time of the experiment.

b. Number of blades on the rotor.

c. Number of blades from which data was taken.

d. Number of ports at which data was taken.

e. Number of data points saved for each blade.

f. Rotational speed of rotor.

g. Number of angle clock counts expected per revolution.

h. Maximum error in the angle clock count at the end of a revolution.

i. Maximum overall deflection and maximum deflection for each blade.

j. One line of operator entered comments.

HP COMPUTER STORE DATA IN DISK FILE COMMAND

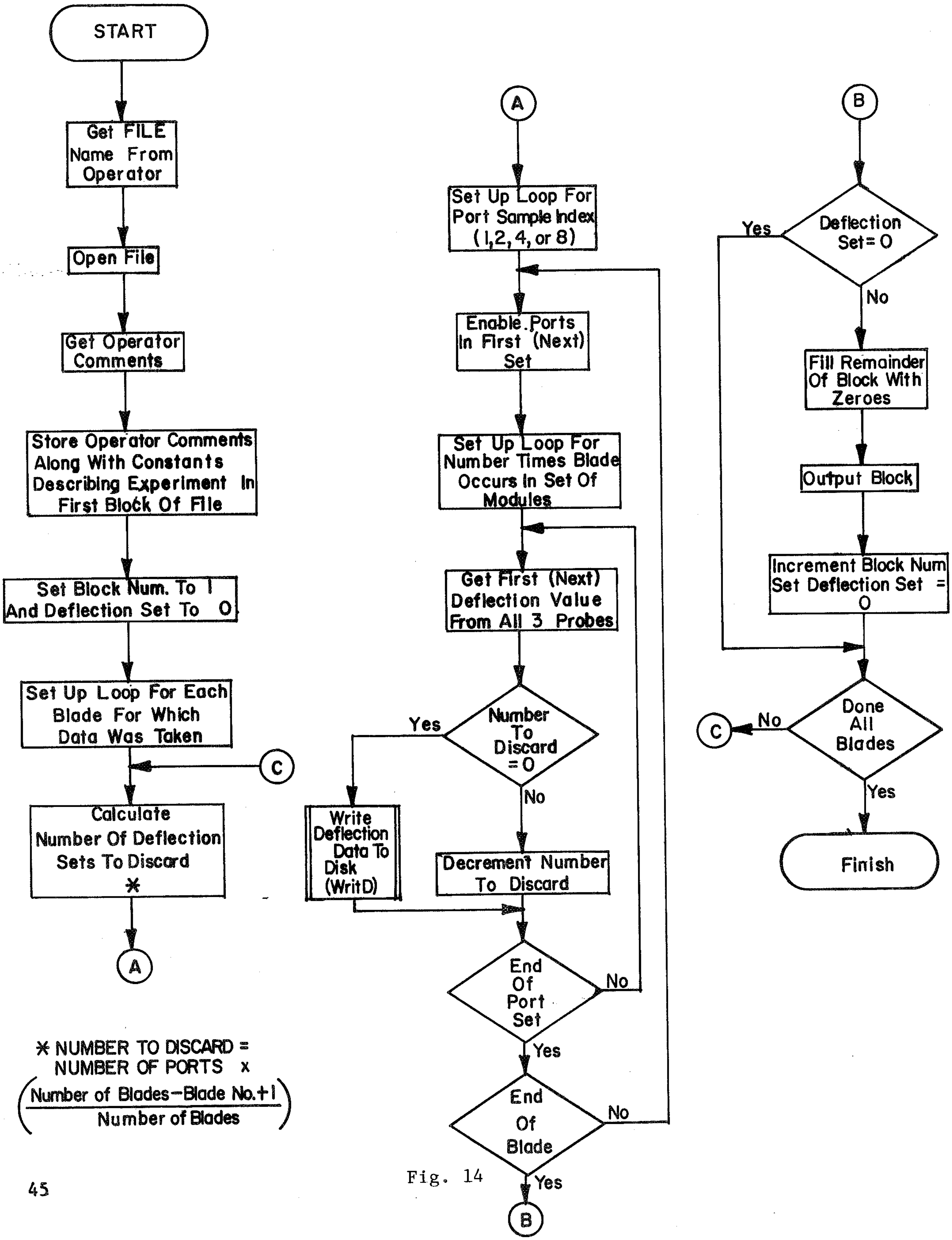


Fig. 14

Display Data from a Disk File (Figure 15 for Flow Chart). The Display Data from a Disk File command will be used to invoke the post-sample display. The operator will first be prompted to enter the name of the file with the blade deflection data. This data will be sorted into time order (from blade order) and stored back on the disk in a special area reserved for this purpose. The operator will then be prompted to enter the blade numbers of the blocks (fig. 16) that he wants to be displayed.

The computer will then start reading the data from the special disk area and will transmit it to the display generator. While the display is being generated the operator will be able to enter commands to change the blades being displayed, terminate the display, or restart the display. When the end of data is reached the display will be automatically restarted after a pause of approximately one second.

Move Data to Fixed Format Disk (Format Shown in Figure 16). The Move Data to Fixed Format Disk command will first prompt the operator to enter the file name of a blade data file and to specify which of 6 fixed areas on the removable platter of the 7990 he wishes the data transferred to. The program will then move the block-by-block to the indicated area.

There are 203 tracks on the removable cartridge of a 7990 disk system, numbered from track 0 to track 202. Each track has 48 sectors (blocks) numbered from 0 to 47. The 6 fixed areas will be assigned to the following locations on the removable disk cartridge.

Area 1	Track 2,	Sector 0	Through	Track 35,	Sector 16
Area 2	Track 35,	Sector 17	Through	Track 68,	Sector 23
Area 3	Track 68,	Sector 34	Through	Track 102,	Sector 2
Area 4	Track 102,	Sector 3	Through	Track 135,	Sector 19
Area 5	Track 135,	Sector 20	Through	Track 168,	Sector 36
Area 6	Track 168,	Sector 37	Through	Track 202,	Sector 5

This command will allow data to be written on removable 7900 disk cartridges and later retrieved by programs running on different HP computers which don't have the File Manager Portion of the RTE system.

Send Data to 2100S. The Send Data to 2100S command will cause the program to get the file name of a deflection data file from the operator and send the contents of the file, a word at a time, to the HP 2100S computer.

HP COMPUTER DISPLAY DATA FROM DISK FILE

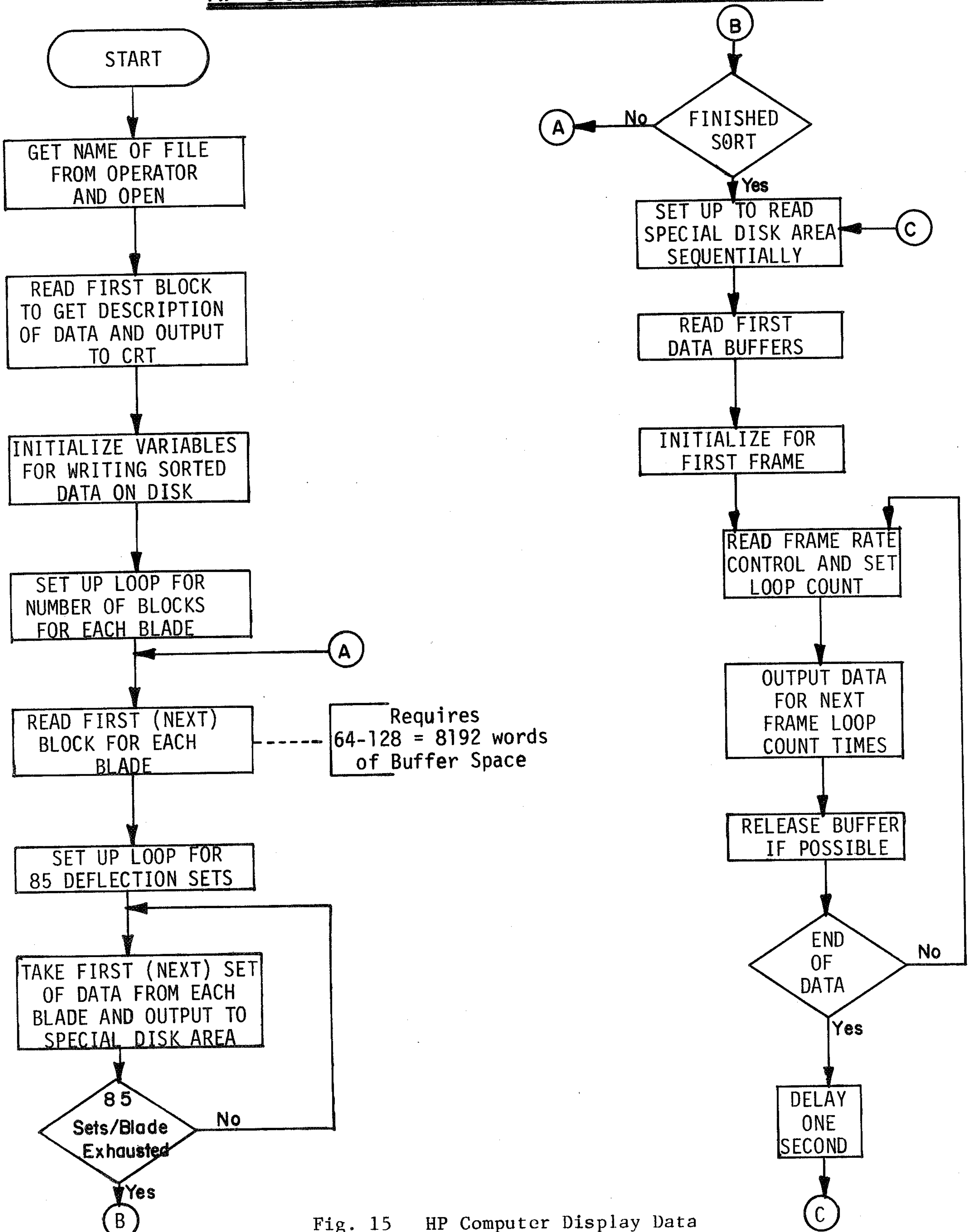
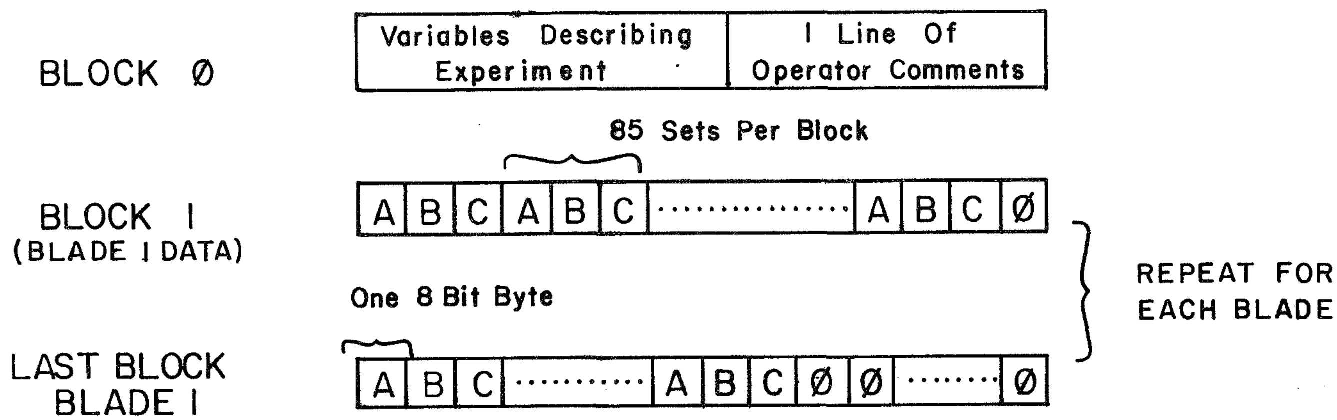


Fig. 15 HP Computer Display Data from Disk File

FORMAT OF DEFLECTION DATA ON DISK

256 BYTE FILE MANAGER BLOCKS



VARIABLES DESCRIBING EXPERIMENT

DATE AND TIME

NUMBER OF BLADES ON ROTOR

NUMBER BLADES FROM WHICH DATA WAS TAKEN

NUMBER OF PORTS AT WHICH DATA WAS TAKEN

NUMBER OF DATA POINTS SAVED PER BLADE

RPM OF ROTOR

NUMBER OF ANGLE CLOCK PULSES PER REVOLUTION

MAXIMUM ERROR IN ANGLE CLOCK AT END OF REVOLUTION

MAXIMUM DEFLECTION AND MAXIMUM DEFLECTION FOR EACH BLADE

Fig. 16 Format of Deflection Data on Disk

BREADBOARD SYSTEM AND TEST RESULTS

The system built during the present contract was intended to test the feasibility of the concept. The contract required that the ability to perform certain functions be verified. They were:

1. Acquire and store data from a sample port at the required maximum sample rate.

2. Acquire and store data at the maximum sample rate from two or more ports simultaneously.

3. Acquire and store data at the maximum rate while skipping every other simulated blade tip.

4. Acquire and store data at the maximum rate while skipping every other sample port.

5. Control and update of the angle clock synthesizer at the required maximum rates.

Additional functions were felt to require specific verification although these functions might be inferred from the proper operation above. These were:

1. Demonstrate full scale count bus
2. Demonstrate hand off of first blade
3. Demonstrate situation where last blade skip is different than other skip (i.e., every other blade for 29 blades).

The concept of window open and closed counters to insure valid data in less than optimum experimental conditions was developed during the contract. Although the demonstration of this concept is not a contract requirement, it must be demonstrated to operate as planned since its inclusion in the system makes it an integral element of the measurement system.

Also during the design of the system, it was decided to switch between two synthesizers rather than attempting to update single synthesizer in under 50 nanoseconds. This decision eliminated the requirement to demonstrate function (5) above.

The test setup is shown in fig. 17. A Futuredata development system for the Z80 microprocessor performed two functions. It could be used in the emulator mode for single DAM in which the board could be checked out using the Z80 and memory of the development system rather than that of the DAM. The development system was also used to simulate the HP computer as a central processor.

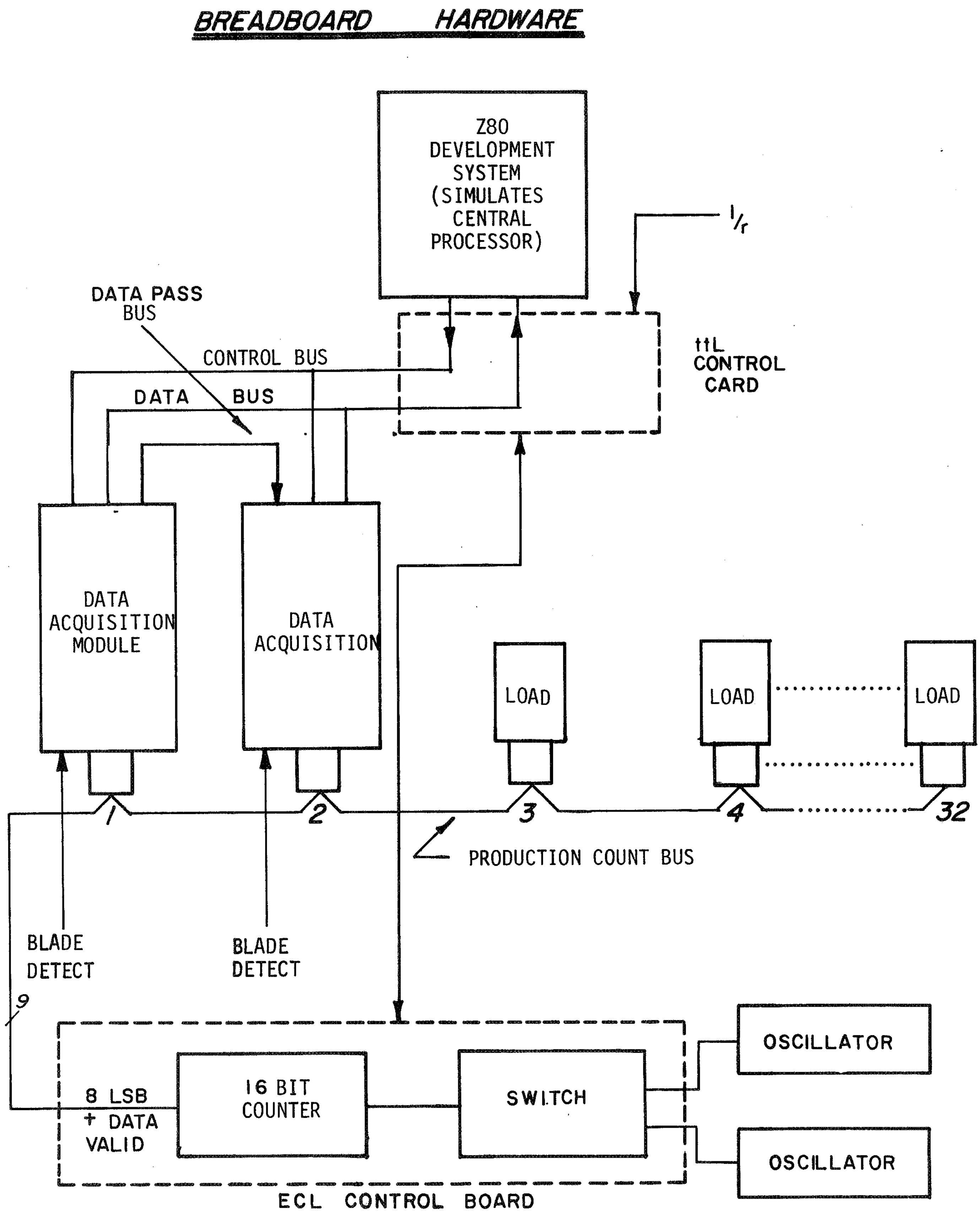


Fig. 17 Breadboard System

The DAM cards include the final circuit design components but are wire wrapped instead of layed out on P.C. cards (as they will be in the final design). The TTL and ECL control boards were wire wrapped as well and they will be the actual cards used in the final system. The layout of the rack was as close as possible to a final 32 DAM rack as it could be without knowing the final size of the DAM card as a P.C. board. The wire wrapped cards also could not be placed on the same spacing as P.C. cards. The spacing between slots 7 and 8 was therefore widened to allow the use of two adjoined cards in these slots. Except for this odd spacing between 7 and 8, the count bus is the same as the production count bus. Fig. 18 through 21 are photos of the breadboard system as set up for test

BREADBOARD FUNCTIONAL TEST

The testing outlined in the contract and the additional test outlined above are system tests. Prior to the system test, each board was functionally tested to insure that it was wired and operated as designed. The test steps are listed below.

1. With the Futuredata system in the emulator mode, exercise the 8255 dual/triple I/O ports on the data acquisition module.

2. Write to and read from the static RAM's in the emulator mode.

3. Write to and read from the 4k dynamic memory in a similar manner.

   NOTE: Step 2 and 3 can be accomplished by progressively moving the test program from its residence in the development system memory into the static and dynamic memories on the DAM.

4. Exercise the programmable counters by programming a count and then inputting a pulse train.

   NOTE: To this point, all circuits on the DAM were exercised except the PROM, the Z-80 and the ECL count bus input.

5. Exercise the four above circuits on the DAM together.

6. Next, write a simple program for execution on the DAM board. Burn a PROM and check the operator of the program in the emulator mode. If the program operates, install the Z-80 and PROM on the DAM and run.

   NOTE: At this point, the complete DAM board hardware except ECL input were checked out.

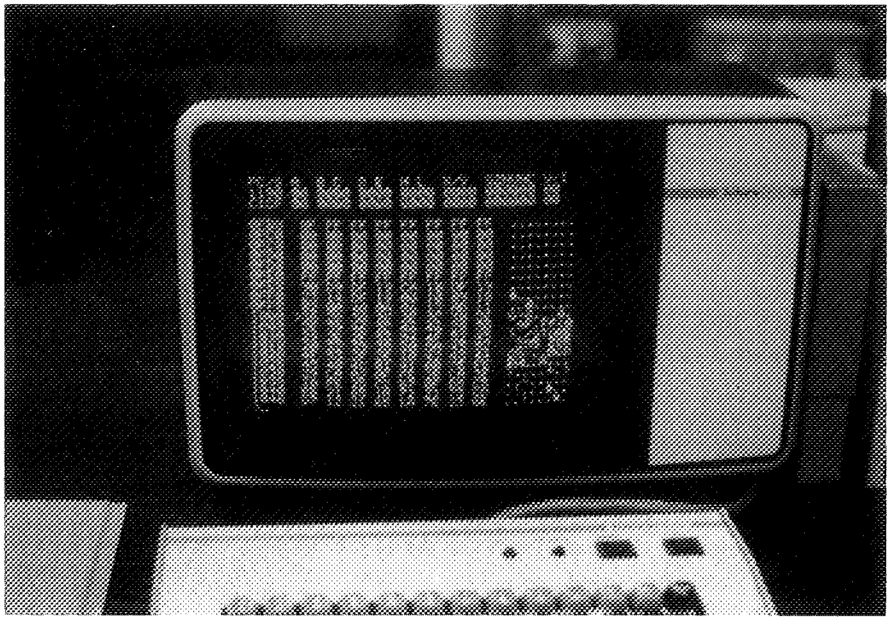


Fig. 18 Development System Screen and Keyboard

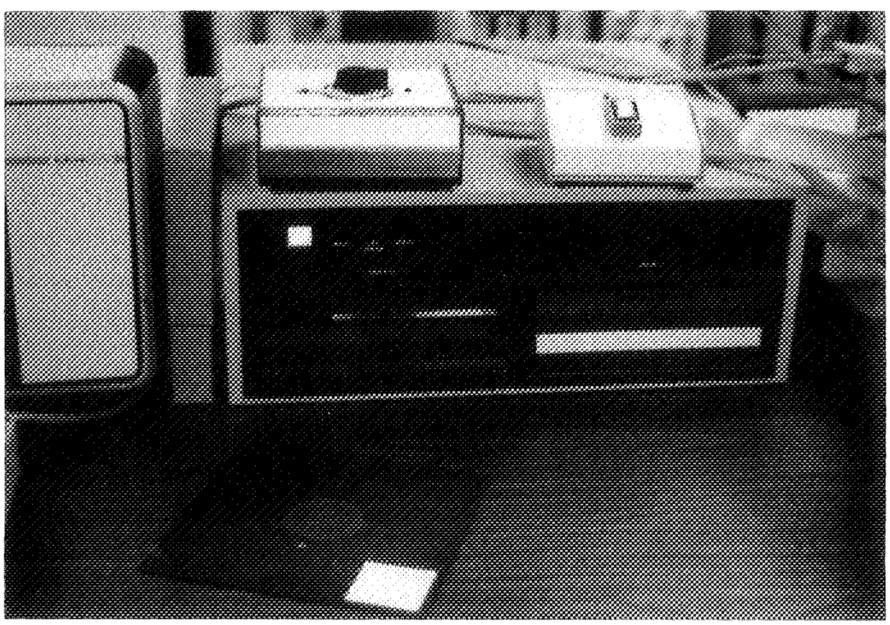


Fig. 19 Development System Floppy Disk,
Prom Eraser and Prom Programmer

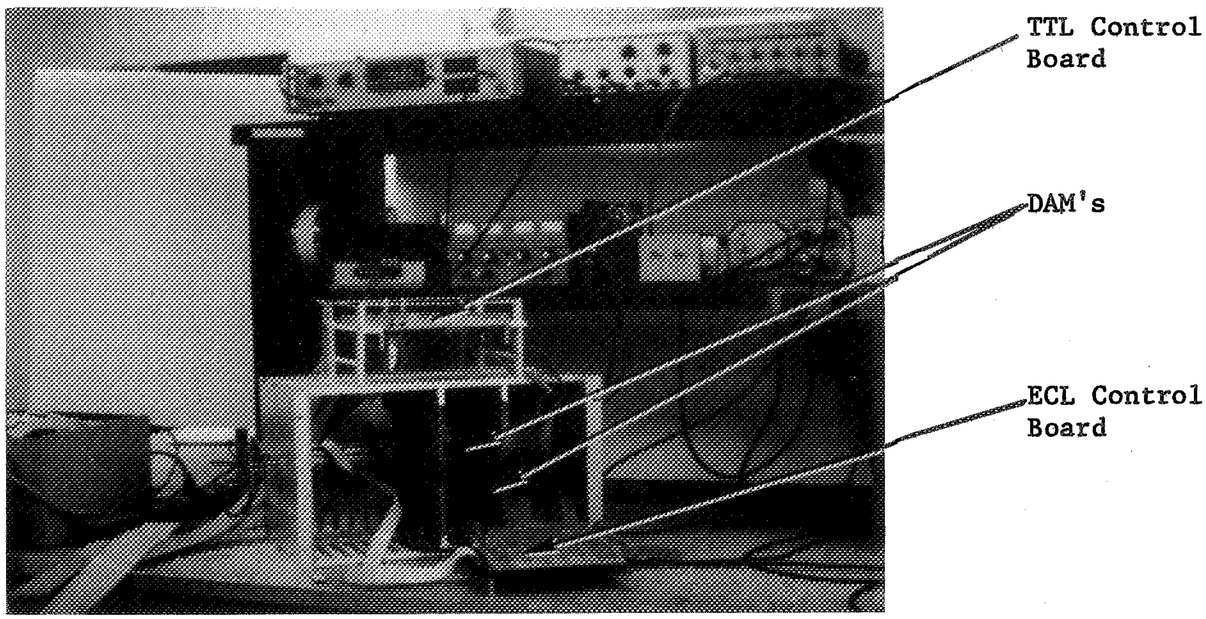


Fig. 20 Breadboard System and Test Equipment

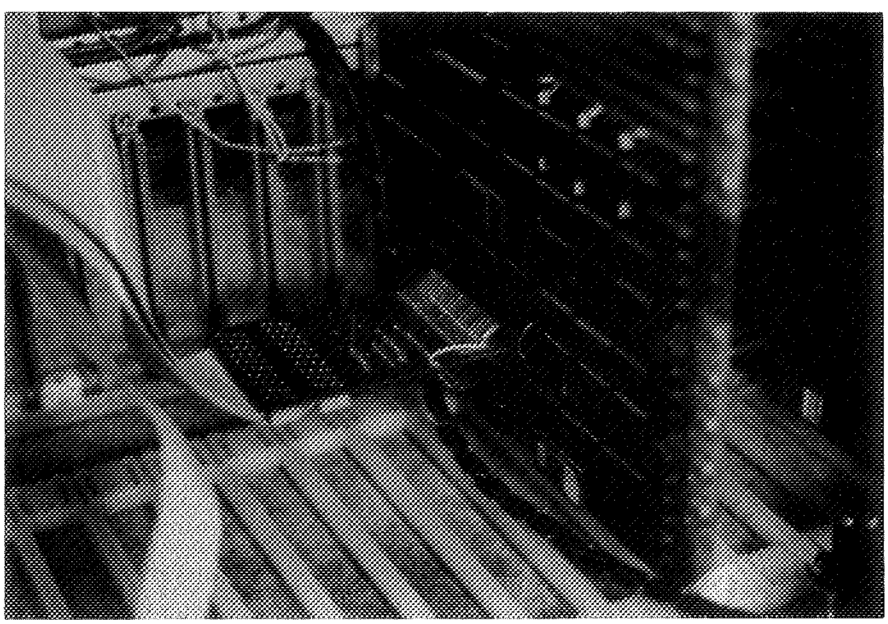


Fig. 21 Data Acquisition Module Board
with Emulator Cable in Place

7. Return to the emulator mode. Enter any command on the control bus using a switch box and a set of lights to check the data bus. Check out all the commands to the DAM. The list of commands accepted by the DAM are shown in Table II.

   NOTE: At this point, the DAM hardware except ECL and software were checked out.

8. Repeat tests 1 through 7 on the second DAM.

9. Now burn the Final Program into the PROM. Check out by repeating Step 7 in emulator mode and then repeat Step 7 using the Z-80 and PROM on the DAM.

10. Mount the two DAM's into the card cage and insert the control card between the Futuredata and the DAM's. Using a program written for the Futuredata that allows setting up a file of commands, and then sending the file over the command lines, repeat the commands previously transmitted by the switch box. This test checks out each DAM's ability to respond when it is addressed and the routing of commands through the control board.

11. Next check out the control card commands that do not involve the DAM's (i.e., load synthesizer, etc.).

12. Check the angle clock portion. At first, the debugging command that allows the angle clock to be incremented is utilized. Next a slow pulse train is utilized as the angle clock counter input. During this testing, the window open and window closed counters are disabled. Blade arrival pulses are fed to both DAM's simultaneously and at a predetermined rate (i.e., angle clock pulse train divided by 16). The printout of the count table from the two DAM's must be identical.

13. The two window open counters and the one window closed counter along with the arm delay counters are now enabled. Again using a slow pulse train and a controlled blade arrival pulse train, two subtests are run with a scope used to monitor the blade detect lag.

    a. The blade arrival pulse train is stopped after N pulses. The window open count closing should now be able to produce pulses for each with a predictable delay showing up in the stored count table. (i.e., the system will "free wheel").

    b. Test a is repeated except that the blade arrival pulse rate is increased (i.e., by 2 or 4). The stored count table should show that it has ignored the extra blade arrival pulses.

FEASIBILITY TESTING

Initial planning for the experimental testing involved setting up rather complex signal sources to act as blade detect pulses while operating the angle clock at various rates. The idea was to run a normalization run, then a data run and examine the data stored in the DAM. This type of testing, requires good synchronization between the angle clock and the blade arrival pulses so that prediction can be made about the characteristics of the data stored. This high speed synchronized multiple pulse train generator was not available and in fact is not necessary to prove the operation of the system.

It is necessary to go through a sample system operation when the Futuredata system is simulating the central control computer to understand the testing description that follow.

In the list of commands accepted by the DAM, Table II, the last command, 40 -- "Include File" allows commands to be sent in sequence to the DAM's. In this way, different files can be set up to perform various tests. Fig. 22 shows the list of commands for a file called GDATA. These commands are explained below. (See also Table II).

19-10,0	The 19 signifies that it is a command to the control board. 10,0 are 4 hex #'s or 16 bits of information. The 1 corresponds to a Stop Experiment Command and results in a reset pulse being generated.
19-B0,0	B signifies a command to stop the angle clock.
19-50,0	50 is a command that divides the angle clock by 1,2, 4,8, or 16 prior to feeding this pulse train to the window closed and window open counters. The last 0 signifies the power of two as a division.
10-C0,0	This starts the angle clock.
1-0	Command 1 sets regular skip count. The zero means that no blades are skipped.
2-1	Command 2 sets the special skip count (i.e., the number to skip after the last blade). This is also set for zero.
3-A	Command 3 sets the group count which is the number of blades for which data will be taken in one revolution. In this case it is told to take data from A (Hex) or 10 blades. Since we are not skipping any blades (commands 1-0 and 2-0). The rotor has 10 blades.

```
19-10,0
19-B0,0
19-50,0
19-C0,0
1-0
2-0
3-A
4-7,0,1,0,2,00,20,00,10
4-8,0,1,0,2,00,20,00,10
5-FF, F9/No. of Revs. = 71/
B-7,A,1,2,3,4,5,6,7,8,A
9-8
A-7
15-8,10,5E
A(16)
17-FF,10,9F,FF(0)/Store 255 zeros/
19-10,0
6-7
6-8
19-20,0
```

Fig. 22 GDATA Test File

4-7,0,1,0,2,00, 20,00,10	Command 4 sets arm delay and window times. The 7 means that we are addressing port 7. The 0,1 is the arm delay telling the port that a blade arriving after 1 clock pulse (= 1 MS) is the first blade. The 0,2 signifies that the window closed time is two pulses. The 00,20 is the window open 1 counter of 20 pulses. The 0,10 is the window open 3 counter setting of 10 pulses. (This set up results in the window counters effectively being disarmed.)
4-8,0,01,02,00, 20,00,10	Same command as above except to port 8.
5-FF,F9	Command 5 sets the local store count which is the same as the number of revolutions for which data will be taken. The hex number FFF9 is the negative of the number of revolutions. In this case even revolutions are desired. $-7_{10} = F9_{16}$
B-7,A,1,2,3, 4,5,6,7,8,9	Command B sets the expected value command. The 7 means we are setting the expected values only for port 7. A means that there are 10 values to be sent and the number 1 - A sets the values to number 1 for 1st blade, 2 for 2nd blade, etc. up to 10 for the 10th blade.
9-8	Command 9 tells the port addressed to accept expected values from the previous port. In this case port 8 then gets the expected value tables from port 7.
A-7	Command A tells the port addressed to send expected values to the next port. In this case port 7 to port 8.
15-8,10,5E	Command 15 tells a port to provide the number in a given memory location. In this case we are commanding port 8 to give us the content of memory location 105E, (location 4190 in decimal). This location is the one before the start of the expected value table storage (the reason for this will be obvious in the next command).
A(16)	This code does not mean command A but rather to repeat command 16 ten times. Command 16 provided the content of the next memory location for the port being addressed. This will result in the readout from port 8 of the 10 expected values that were put into port 7 and sent from port 7 to port 8.

17-FF,10,9F,FF (0)	Command 17 stores information into memory. FF means all ports respond 10,9F is the memory location which is the first location for blade arrival data FF(0) sends 255 zeros.
19-10,0	Reset.
6-7	Tells port 7 to take data from probe.
6-8	Tells port 8 to take data from probe.
19-20,0	Starts the experiment.

The above series of commands sets up a test that takes data from every blade of a 10 bladed rotor for 7 revolutions or a total of 70 numbers. Since the arm delay for the first blade has been set identically, both ports will think that the first blade arrival pulse is the first blade and they will accept the data. An expected value table has been sent and the ability to move the table from one port to the next will be checked by reading out the table from 8 after storing it in 7 and moving it to 8. The memory is set to zeros so that later if numbers are in these locations, then the experiment must have placed them in memory. Finally, we tell ports 7 and 8 to start to take data. The next thing that must happen is for the system to receive a 1/rev. signal then ≃ 1 Ms later data will start to be taken. Since both ports are set up identically, both ports should have exactly the same data if there are no errors.

To test to see if correct data were being taken, an experimental set up as shown in Fig. 23 was used. The synthesizer used has a maximum input frequency of 150 kHz. This was taken as the angle clock. A divide by 8 output or 18 750 Hz pulse train was used for the blade arrival pulses. With these inputs, file GDATA was called and then the 1/rev. was sent to the system. Another program was then used, RDATA (Fig. 24) that printed out 80 numbers on the screen. (Unfortunately except for assembly listing, the printer could not be addressed from the Futuredata system). The results are shown in Fig. 26. The data is identical from port 7 and 8 as predicted and the increment in angle clock counts for each blade detect is 8.

The test was rerun with the 150 kHz divided by 7 resulting in a blade arrival rate of 21.428 kHz which exceeds the maximum sample rate. The results were the same as above except that the interval was seven instead of 8. This proves that the coding of the critical loop of the microprocessor is capable of operating at a faster rate than the maximum sampling rate. Incidentally, in both of these tests the data taken consisted of 70 samples proving the system's ability to limit total data gathered.

The next test involved running the angle clock at its maximum rate (≃25 mHz) and the blade arrival pulse timer at its maximum rate of 19.2 kHz. In this case, the two signals were not synchronized in any way so that there was no

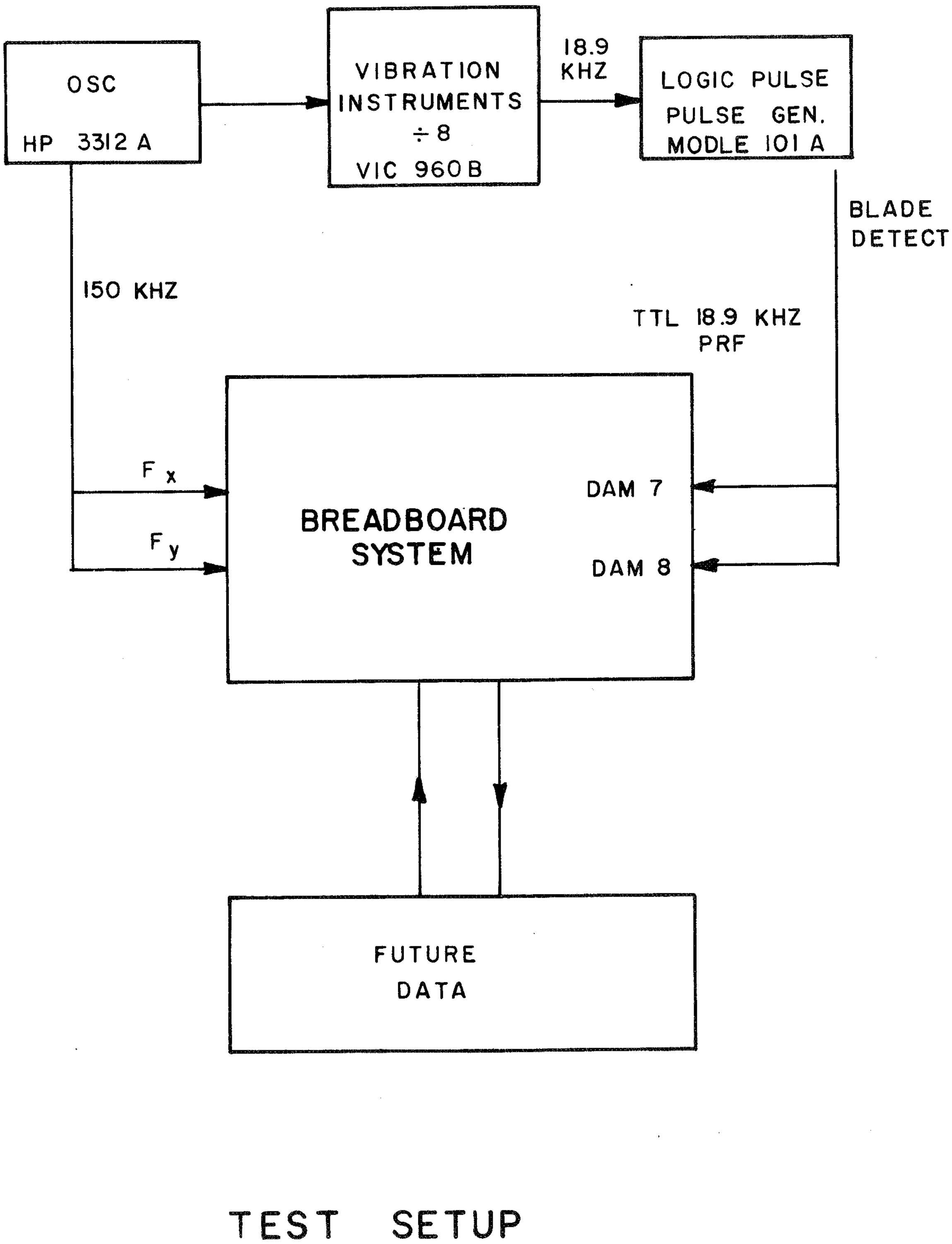


Fig. 23 Test Set Up

```
19-10,0
15-7,10,9E
50(16)
15-8,10,9E
50(16)
```


Fig. 24 RDATA Test File

Port 7

4C	54	5C	64	6C	74	7C	84	8C	94
9C	A4	AC	64	BC	C4	CC	D4	DC	E4
EC	F4	FC	04	OC	14	1C	24	2C	34
3C	44	4C	54	5C	64	6C	74	7C	84
8C	94	9C	A4	AC	B4	BC	C4	C4	D4
DC	E4	EC	F4	FC	04	OC	14	1C	24
2C	34	3C	44	4C	54	5C	64	6C	74
00	00	00	00	00	00	00	00	00	00

Port 8

4C	54	5C	64	6C	74	7C	84	8C	94
9C	A4	AC	64	BC	C4	CC	D4	DC	E4
EC	F4	FC	04	OC	14	1C	24	2C	34
3C	44	4C	54	5C	64	6C	74	7C	84
8C	94	9C	A4	AC	B4	BC	C4	CC	D4
DC	E4	EC	F4	FC	04	OC	14	1C	24
2C	34	3C	44	4C	54	5C	64	6C	74
00	00	00	00	00	00	00	00	00	00

Fig. 25 Data Print Out

reproducible increment in the data stored. The test must therefore consist of starting both modules at the same time and comparing the data to show that the data stored in both modules was identical. In the actual operation of the test, the data was not exactly identical; however, it varied only in the least significant bit.

At this point, the test requirement should be reviewed and a brief description of the test run given and the results described.

1. Acquire and store data from the sample port at the required maximum sample rate.

   Test: No tests were performed which exercised only one single port.

2. Acquire and store data at the maximum sample rate from two or more ports simultaneously.

   Tests: Two tests were run. One where the angle clock was at 150 kHz and the blade pass at 150 000/7 = 21 428 Hz (over the maximum sample rate of 19 200). The second test utilized an unsynchronized angle clock at 25 mHz and the blade arrival pulse train at 19 200 Hz.

   Results: In the first test the data was identical in both ports and the increment between data samples was seven counts on the angle clock.

   In the second test the data was identical in both ports within the least significant bit (i.e., count stored sometime varies by one). This has been attributed to the breadboard ECL clock used.

3. Acquire and store data at the maximum rate while skipping every other simulated blade tip.

   Test: The angle clock was run at 150 000 Hz and the blade pass at 150 000/7 = 21 428 Hz. The test was programmed for 10 blades. The regular skip count was set to 2 to take data from every third blade while the special skip count was set to skip 0 blades. Data should be taken from blades 1, 4, 7, 10, 1, 4 etc.

   Results: The data in each port was identical since the arm delay was still set to 1 microsecond. The interval between blades 1, 7 and 10 was verified to be 7 x 3 = 21 while the interval between 10 and 1 was verified to be 7.

4. Acquire and store data at the maximum rate while skipping every other sample port.

Test: Angle clock and blade pass frequencies are as in Test c. Ten blades were used and no blades were skipped. Command 6 was given only to port 7 while command 7, take data from previous port, was given to port 8.

Results: Seventy numbers with an interval of 7 should be taken in port 7 then its data should be sent to port 8 where 70 more samples are stored. The key here is that the interval between the 70th sample at port 7 and the first sample at port 8 was also 7.

5. Control and update the angle clock synthesizer at the required maximum rate.

Tests: It was agreed that if two synthesizers were used and the output was switched each revolution then it was not required to demonstrate that a synthesizer could be updated in 3.3 Ms. The test run was simply to switch between two inputs to the switch and check the output to insure a smooth switch.

Results: A smooth switch was observed on a scope except at the high rate of 25 mHz. Some problem was encountered at this rate; however, it was felt that this was a minor adjustment problem in the ECL switch.

6. Demonstrate full scale count bus.

Test & Results: The actual full scale count was used for all tests.

7. Demonstrate handoff of first blade.

Tests: The time between blade arrival pulses when operating at 21 428 Hz is 47 microseconds. The microprocessor clock divided by 2 ($\phi/2$) input to the arm delay counter has a period of 0.8 microseconds. If the arm delay is set at 1 pulse for port 7 and 120 pulses for port 8 then data will not start at the same time in each port.

Results: For the above data the first lines of the stored data started as shown below indicating port 8 skipped two blade arrivals (0.8 x 120 = 96μsec).

Port 7	52	59	60	67	6E ...
Port 8	60	67	6E	75	7C ...

Other arm delays and blade arrival frequencies were tried with the predictable results.

8. Demonstrate situation where last blade skip is different than the skip.

   See Test c.

The demonstration of the window closed and window open counters were evaluated during the functional test of the DAM's. It was difficult to show one blade arrival pulse missing or an extra noise pulse for an actual pulse train. The part that could be demonstrated was that if a test was set up and the 1/rev. signal set, but no blade arrival pulses sent, the system would free wheel. The relationship between window times and the data interval had a rational relationship.

In addition to the above, simulated normalization runs were conducted and calculations of blade deflections made. All results were as predicted.

SUMMARY AND CONCLUSIONS

1. The turbojet blade vibration data acquisition system has been designed as envisioned by NASA in the Request for Proposal.

2. During program reviews with NASA personnel, it became apparent that some provision should be included in the system design for missing blade pulses and extra noise pulses at a given port. This was done and included in the design.

3. Timing considerations based on circuit and software analysis showed that the system will operate as planned.

4. A system consisting of the control cards and two data acquisition modules was breadboarded for feasibility testing.

5. Feasibility testing was conducted using a microprocessor development system to simulate the final system control computer. Tests were conducted using simulated blade arrival pulses.

6. Several critical functions were identified that should be tested in addition to those identified in the contract.

7. All tests were successfully completed and the results insure that a final system built to the design will operate as planned.

RECOMMENDATION

One simple recommendation results from the successful completion of the feasibility testing. Since the feasibility of the Turbojet Blade Vibration Data Acquisition System has been demonstrated, fabrication of the final full scale system should be initiated.