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DIGITAL SYSTEM FOR DYNAMIC TURBINE ENGINE BLADE DISPLACEMENT MEASUREMENTS

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DIGITAL SYSTEM FOR DYNAMIC TURBINE ENGINE BLADE DISPLACEMENT MEASUREMENTS

by

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ABSTRACT

An instrumentation concept for measuring blade tip displacements which employs optical probes and an array of micro-computers is under development by the NASA-Lewis Research Center. The system represents a hitherto unknown instrumentation capability for the acquisition and direct digitization of deflection data concurrently from all of the blade tips of an operational engine rotor undergoing flutter or forced vibration. System measurements are made using optical transducers which are fixed to the case. Measurements made in this way are the equivalent of those obtained by placing three surface-normal displacement transducers at three positions on each blade of an operational rotor.

The difficulties normally associated with strain gage life and durability can be reduced. The costs associated with the mounting of the strain gages and the installation and maintenance of slip rings can be minimized or avoided.

The system reported herein directly digitizes a minimum of a 2048 point time-deflection history for each of the three measurement locations on each blade. For a 64-bladed rotor operating at 18000 RPM, 393216 data points are taken in a minimum sample period of 70 milliseconds. Alternate modes of operation can expand the sample period and/or acquire additional data from only selected subsets of the blading. Provisions within the design concept automatically correct the data points for rotor speed variations, nominal blade-to-blade and instrumentation probe misalignments, and either blade data points that are missed or extraneous blade data, generated by foreign objects passing the optical probes.

Introduction

Experimental determinations of blade vibration phenomena in gas turbine engines are extremely important to the advanced development of these engines. Many aspects of these vibrations are difficult to adequately predict or measure in any quantitative fashion. These include certain aspects of forced vibration response, blade flutter phenomena and complex engine structural interactions which occur during transient excitations. Experimental methods are needed to refine analytical tools and to develop advanced engine designs which meet the constraints imposed by system life margins, engine operating envelopes, required maintenance schedule, and safety. Advanced turbine engine development will require a broader accounting for blade vibration phenomena as future design goals are met for increased performance, decreased weight, fuel economy, and minimized user cost.

Traditionally, blade vibration phenomena on rotating members have been studied using strain gages. Signals generated on the blades are passed through either multi-channel sliprings or telemetry devices. Significant problems with these approaches include the degradation or loss of strain gage signals due to hostile operating environments. Furthermore, the number of measurement points is limited by the capacity of available slip-ring devices. It is very difficult to quantitatively determine actual vibration patterns on rotating bladed stages with the limited number of measurement points available with strain gage technologies. In part, this is due to the complexity of these vibration patterns and the need to monitor many points in order to fully characterize these motions.

Holographic studies have shown that bladed rotors tend to vibrate with complex motions. These motions are characteristic of the total bladed assembly rather than characteristic of a single blade's behavior. The holographically generated modal deformation pattern shown in Figure 1 is for a rotor mounted statically on a test stand and excited at a given natural frequency. Some of the blades are exhibiting torsional vibrations while other of the blades are exhibiting bending vibrations. Yet, all of the blades are nominally identical and all are vibrating at the same frequency. All of the blade vibrations are coupled and result in a common modal behavior. This behavior is typical for bladed rotor assembly vibration modes and, because of this, many points must be examined when considering blade vibration phenomena in gas turbine stages.

These complex responses become increasingly more complicated as the bladed rotor is spun at operating speeds. The effects of aerodynamic and centrifugal loading and non-harmonic excitation result in very complex deformation patterns. Experimental methods are required for the measurement of many points on these rotating systems in order to develop a better assessment of the dynamical state of the entire assembly. Holographic imaging methods with optical de-rotating prisms provide an excellent source of qualitative modal information for rotating stages which are visible in line-of-sight (1). Strain gaging methods are limited when considering a many-bladed structure because of the number of strain gages required and the limited number of channels available on slip-ring devices or telemetry systems.

Techniques have been developed at the NASA Lewis Research Center (LeRC) for measuring blade vibrations using optical sensors fixed in the casing (2). Aliased single degree of freedom

N80-14113 #

vibrations of all the blades on an operating engine have been successfully sampled using these techniques.

The system described as the subject of the current paper acts to co-ordinate and assemble the inputs of many such optical probes in order to monitor all of the blades on a spinning rotor. Several points on every blade may be monitored in order to develop a guantitative measure of the overall rotor response. The system concept has been carried to the detail design stage and has been breadboarded and tested under contract to Shaker Research Corporation (3). Currently, final design and fabrication is being initiated.

Deflection Measurements with Optical Sensors

Blade deflections are measured with optical sensors which monitor the passage of blade edges. The optical sensor assembly or probe consists of a light source and a light receiver. Light from the source is reflected from a passing blade edge to the receiver and causes an electrical pulse output to be generated. The time at which this pulse should occur for a quiescent blade may be determined by other means. The actual blade deflection along the direction of blade motion (i.e. circumterentially) when sampled can be approximated by subtracting the predicted blade arrival pulse time from the actual blade arrival pulse time. The deflection can then be determined from a knowledge of the speed at which the blade passes the probe. Blade edges which can be monitored in this manner include leading and trailing edges in special test facilities and also blade tips in more general test facilities. Application to operational engines is most readily accomplished by monitoring blade tips only, with probes which do not interfere with the air flow through the stage.

Time measurements are best made using a clocked digital counter. Each successive clock pulse represents an additional increment in time and advances the counter by one. The probe generated blade detection pulse acts to strobe the current counter value into a storage register which represents the time at which the blade edge was sensed. These data may be used in further data reduction. Once each revolution, the accumulated count is cleared and the counter is restarted. Ideally, if the rotor speed were absolutely constant and a given blade were absolutely quiescent, then this blade would always register the same count as it passed a particular probe. Variations in this measured count would represent blade deflections from the quiescent condition. The rate at which the counter is clocked determines the resolution of the system. For this system, the clock can run as high as 24 MHz with a minimum deflection resolution of 0.0008 inch (for a 20-inch diameter operating at the maximum rotor speed). Coarser resolutions may be obtained by changing the clocking rate to change the total number of counts which occur during a rotation of the rotor.

Since the rotational speed of the rotor cannot be expected to always remain exactly constant, a slight variation of the basic concept is warranted. If the clocking rate of the counter is varied in conjunction with variations in the rotational speed, a constant number of counts will occur during each rotor revolution. The counter may now be thought of as counting increments in angular position rather than increments in time and a given accumulated count represents an absolute angular position with respect to a once-per-revolution reference pulse. The principle of making measurements in this way is known as the angle clock principle (2). The angle clock may be generated using commercially available frequency synthesizers with the rate adjusted once each revolution in order to maintain a constant number of counts. For slowly varying rotational speeds, two synthesizers may be used in tandom - so that one may be updated as the other is providing clocking pulses to the angular position counter.

In order to develop a complete picture of the blade vibrations of an operational rotor, many optical probes are required. Three probes, labeled A, B and C may be arranged as shown in Figure 2 to scan for blade edge deformations. The set of probes have to be repeated many times around the circumference in order to meet fundamental sampling rate requirements. For simplicity, we will refer to each repeated group of three probes as a sample port. Each sample port takes the same information from every passing blade at the three locations identified as A, B and C as shown in Figure 2.

In the limiting case, we want to study a 20 inch diameter rotor with 64 blades operating at 18000 RPM. For this case, each probe samples a blade passage at an average rate of 19200 Hz. Desired alternate modes of system operation and other sampling rate considerations require a total of 32 ports. For these conditions, the net sampling rate of the system is about 2 MHz. The samples can become highly asynchronous depending on how many blades are on the current test rotor and which alternate mode of operation is desired. Because of the shear volume and rate of data generation, a microprocessor array is used to collect the data. This array contains one microprocessor with a 4k memory for each probe for storing blade deflection data.

A set of 64 numbers which represent the undeformed (or expected) angle counts for each blade in the test rotor is stored locally within each microprocessor. These expected values are generated in a normalization run on a blade-by-blade and a port-by-port basis. Each probe at each port has an associated expected value table for each of the blades in the rotor. These values are generated experimentally by averaging a long sample of blade deflections for the rotor under low speed, minimal vibration conditions. In this manner, the system automatically corrects for blade-to-blade and port-to-port dimensional misalignments. The expected values are subtracted from measured angle counts in order to determine actual deflections.

Figure 3 is an example of a hypothetical six bladed rotor operating in a four sample port system. As each blade passes a probe blade deflection data is stored in sequence in the associated microprocessor memory, as shown in Figure 3. When the deflections for a given blade are 'played back' and reassembled, a sampled time history of that blade's vibration (as it passed the sample ports) can be determined as shown in Figure 4. In this manner, the vibration histories at each of three points on every rotor blade tip may be reconstructed.

Design Goals

The system is configured to meet blade data acquisition requirements for a hypothetical rotor consisting of 64 blades and rotating at 18000 RPM. For this rotor we want to resolve blade deflections as small as one thousandth of an inch. Further, prior experience indicated there will be few vibrations at frequencies greater than 3500 Hz. At least 24 sample ports are required for sampling the blade vibrations without aliasing a 3500 Hz vibration signal. The chosen number of 32 ports for the system provides a 30% sampling margin and permits some unique alternate modes of operation.

The use of a microcomputer array allows adjacent array elements to share memory so that selective blade monitoring operations can be accomplished. For example, the system can be configured under software control to only monitor a selected subset of the rotor blading. Time-deflection histories for these blades may now be reconstructed which cover a longer time period. This results in a proportionally better frequency resolution for these data records (4). Another mode of operation involves 'turning-off' a set of the sample ports by ignoring any blade detection signals which occur at the associated probes. The memories of the microprocessors associated with these probes can then be slaved to the active port processors in daisy-chain fashion. This mode of operation improves the frequency resolution of the system by again providing records that span a greater length of total time. However, under these conditions, the system takes blade vibration data at less than the maximum rate. Because of this, the system is somewhat more limited in sampling high frequency vibrations without special data reduction methods due to aliasing possibilities (4). These modes of operation may be mixed in order to best match the requirements for a given vibration test. The use of 32 ports optimizes the flexibility of turning off selected sets of ports and sharing port memories for monitoring blades. It is possible, for example, to turn off all of the ports but one and to monitor only one blade by slaving the memories of all of the processors. Some examples of other possible modes of operation and characteristics of the data sampling are given in Table 1.

System Configuration

The system is configured to be generally useful for a variety of rotor configurations and test conditions. Figure 5 is a block diagram of the system bus arrangement and major functional units. Two synthesizers are used in tandom to provide the angle clock count. These synthesizers are adjusted by a control computer to maintain a constant number of angle clock pulses per rotor revolution. An emitter coupled logic (ECL) control board selects the active synthesizer, and 'broadcasts' the angle clock to each of the 96 data acquisition modules (DAM's) which make up the microcomputer array. At most only one count per revolution is lost during the switching between active synthesizers. The DAM boards are arranged in groups corresponding to probe positions (at the A, B or C level). Within each group of 32 DAM boards data may be passed in daisy-chain fashion. This is denoted by the data pass and arm lines shown in Figure 5. Each of the DAM'S are uniquely associated with an individual probe.

The DAM's and frequency synthesizers are controlled by a transistor transistor logic (TTL) control board which is driven by the control computer. The control board interface acts to program individual DAM's to function in various modes and controls the passage of data to and from the DAM's.

Arming Function

An orderly and well-controlled start up sequence is required for the system data taking operation. Blade data are stored in sequence as taken in each DAM memory, on a point-by-point basis as each blade in turn passes the associated probe. The integrity of this sequence of data is essential to the unraveling of the stored data (eg., as shown in Figures 3 and 4). If a data point is ambiguously stored, the remaining data become useless. This is why an orderly start up procedure is essential.

For example, suppose that a 37 bladed rotor is to be tested using a 32 port system. In Figure 6, it is clear that at least one blade will always be ambiguously located at one side or another of an associated sample port-depending upon how it is vibrating. Because of this effect, there is simply no single instant at which we can turn on all of the sensors and take unambiguous data records.

Shaker Research (3) devised an arming function for the DAM's which eliminates this potential ambiguity. The arming function is accomplished by arming successive DAM's in sequence. At some programmed time after a given DAM finds the first blade, the next successive DAM is armed, or 'turned on'. This module then takes data from the next blade which arrives. After it senses this next blade, it arms the next DAM in sequence. Proper choice of the arm timing insures that all of the modules start taking data with the same reference blade.

The first DAM in the arming sequence is armed by the TTL control board to begin taking data at a given time interval after the once-per-revolution pulse occurs. Once any of the DAM's are armed they take data continuously until the specified portions of their memory is filled or until they are reset by the control computer as illustrated in Figure 3.

Data Windowing

Once the system is operating, various conditions may occur which will influence the data integrity by causing the system to either miss blade pulses or to add blade pulses due to extraneous reflections. In order to insure that only one blade detection pulse occurs during the proper angle clock interval slot a data windowing function is required. The data window is 'closed' when no valid data should be detected and 'opened' in the interval over which a blade detection should occur.

The window open-close logic is generated by three counters which act to allow only one sensor pulse to pass through the system during the open interval. Furthermore, if a blade arrival pulse is missed (due to a marginal reflectively), the window logic creates an apparent blade detection pulse so that data are stored in proper sequence - even though the missed data point will be generated arbitarily. Finally, the window logic acts to resynchronize the window timers to detected blade data. This prevents the open window from drifting out of the proper sequence. Window drift could otherwise occur because of the integral nature of the counters (eg. a fractional count may be required for some conditions to keep the window interval exactly in synchronization with the blades).

The logic is somewhat involved and is illustrated in Figure 7. To understand the operation, the following signal and counter names are adopted:

BA	Blade Arrival Pulse, this is the blade detection signal which could be valid, noise or a missed (pulse).
WCC	Window Closed Counter. BA is not accepted during WCC valid except in one special case.
WOC2	Window Open Counter -- Set to be valid during a count roughly equal to the possible angle over which the blade can be expected.
WOC1	Counter set to be valid for an interval twice that of WOC2.
ABA	Apparent Blade Arrival. Signal accepted by system as a blade detection pulse.

The following definitions are used:

BA starts or restarts WCC and generates ABA 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 already 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 and WOC2 are started by WCC counting out.

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

Figure 7 shows the case where the blade pulse is missing and the case when extra noise pulses arrive. Note the ability of the "window" to drift in both directions to its proper place after a serious upset.

System Operation

A schematic of the DAM which incorporates all of the features for windowing, arming, multi-mode operation and control is shown in Figure 8. The angle clock interface which includes the count bus and the data valid (DAV) signal are implemented in ECL. The remaining functions are implemented with TTL level devices. Blade arrival counts are buffered by a first in-first out register (FIFO). Window counters are derived from the angle clock and the arming counter is derived from the processor clock. Programmable I/O ports are used to communicate with the control board, adjacent DAM boards and to read a board location tag from the back plane wiring. The board location tag is used by each DAM to define which board should respond to a polling operation from the control computer. An on-board programmable read only memory (PROM) contains the various processor routines which allow the DAM to perform in its various modes of operation. The random access memory (RAM) consists of two portions. The 4K (or 4096 word) block of memory is used to store blade deflection data. The remaining RAM is used to store data tables for normalizing blade data and for containing a variety of logical flags for system operation.

In addition to the modes of operation already discussed there are two more which are used to simplify user operation and monitor system performance. The diagnostic mode is used to pass simulated blade deflections from the control computer for functional DAM checking as well as other basic DAM function checks. A pre-sample mode is used to determine the best time to take data from the spinning rotor. In this mode only one port is activated and the blade activity at that port is continuously monitored on a graphic device by the operator. This allows the operator to set system parameters, such as the resolution limits, in real time. Further, with the entire system in a otherwise operational state, the operator need only push a single button to quickly gather data for such rapidly occuring events as flutter instability vibrations.

Finally, as experience is gained in the use of the system new functions or modes of operation may be readily implemented. Due to the flexibility of the modular components within the data acquisition system - many operational system changes may be readily implemented by simply changing the PROM and control computer software. For example, it should be relatively easy to provide an auto-triggering mode so that a full data run is made whenever a vibration level threshold is crossed, or to continuously take data until some interesting phenomena is observed.

Conclusions

The use of an array of microprocessors to coordinate, collect and correct the data generated by an array of photo-optical probes provides a convenient way of managing large volumes of blade vibration data. The equivalent of three surface-normal blade displacement transducers on every rotor blade is possible. This provides a quantitative picture of rotor vibration modes with non-contacting probes. The system described provides for modularized software controlled functions which can be readily upgraded by changing the controlling software.

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TABLE I

EVALUATION OF SYSTEM PERFORMANCE

System characteristics for different experiment setups.

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

[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 available per port.

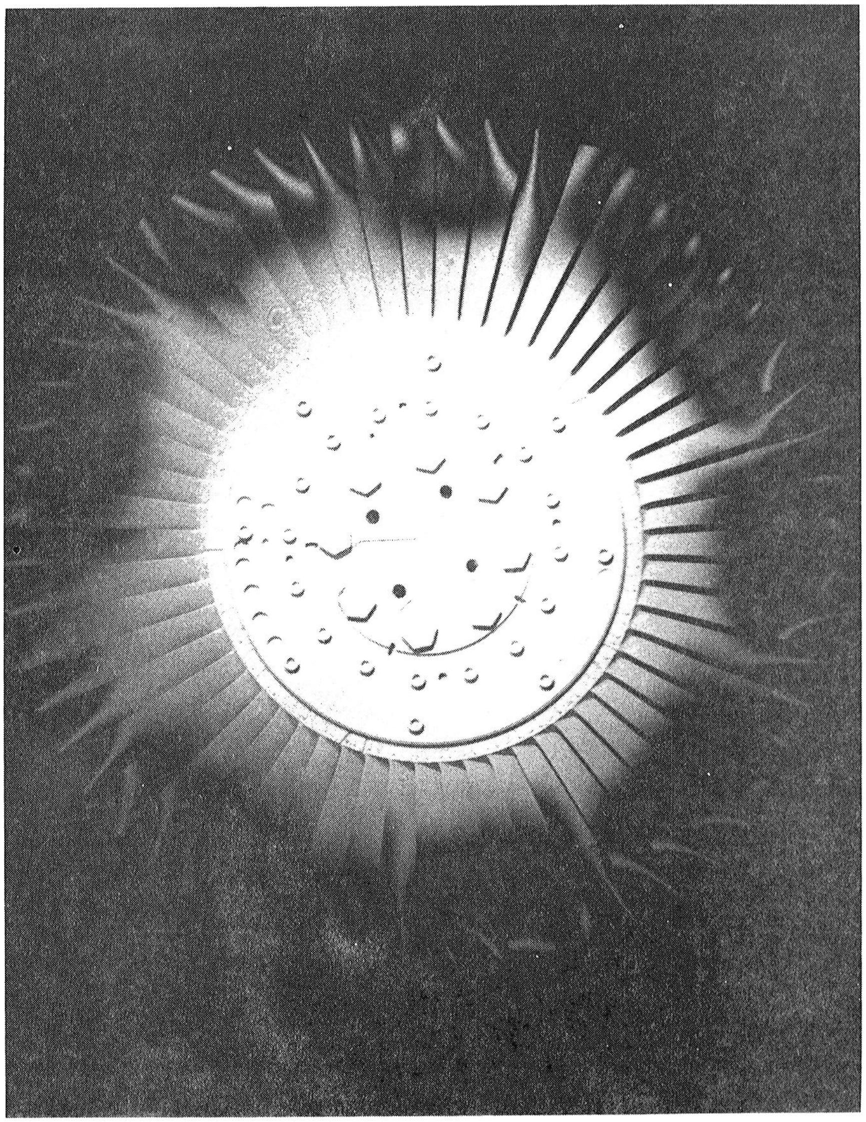
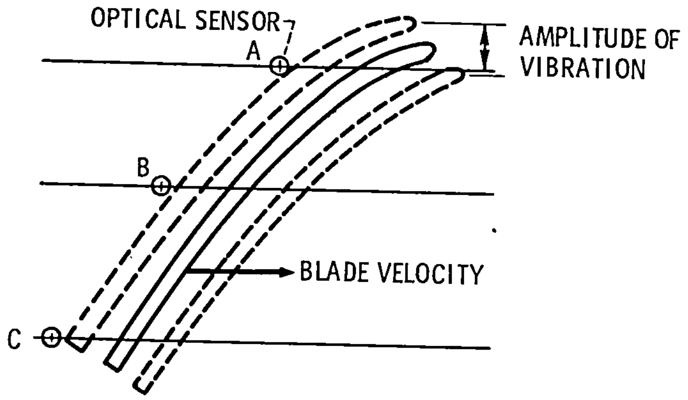
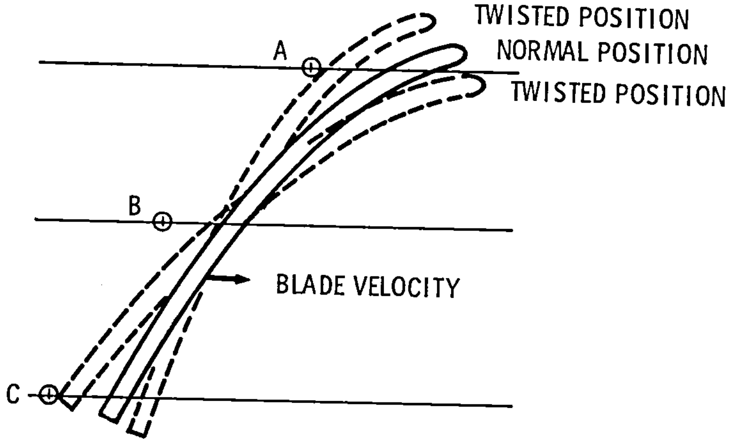


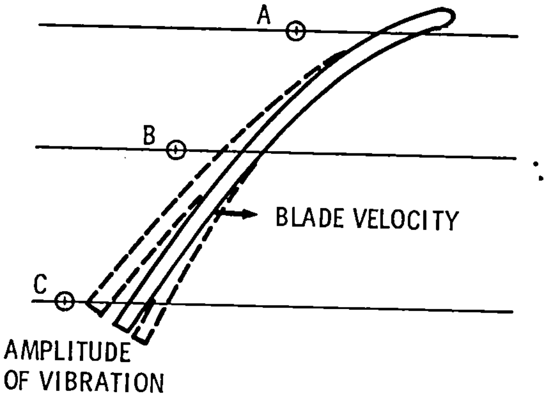
Figure 1. - Hologram of a bladed rotor mode.



(a) BENDING.



(b) TWIST.



(c) CAMBER LINE DEFLECTION.

Figure 2. - Blade motions observed with 3 probes looking at the blade tip (radially inward).

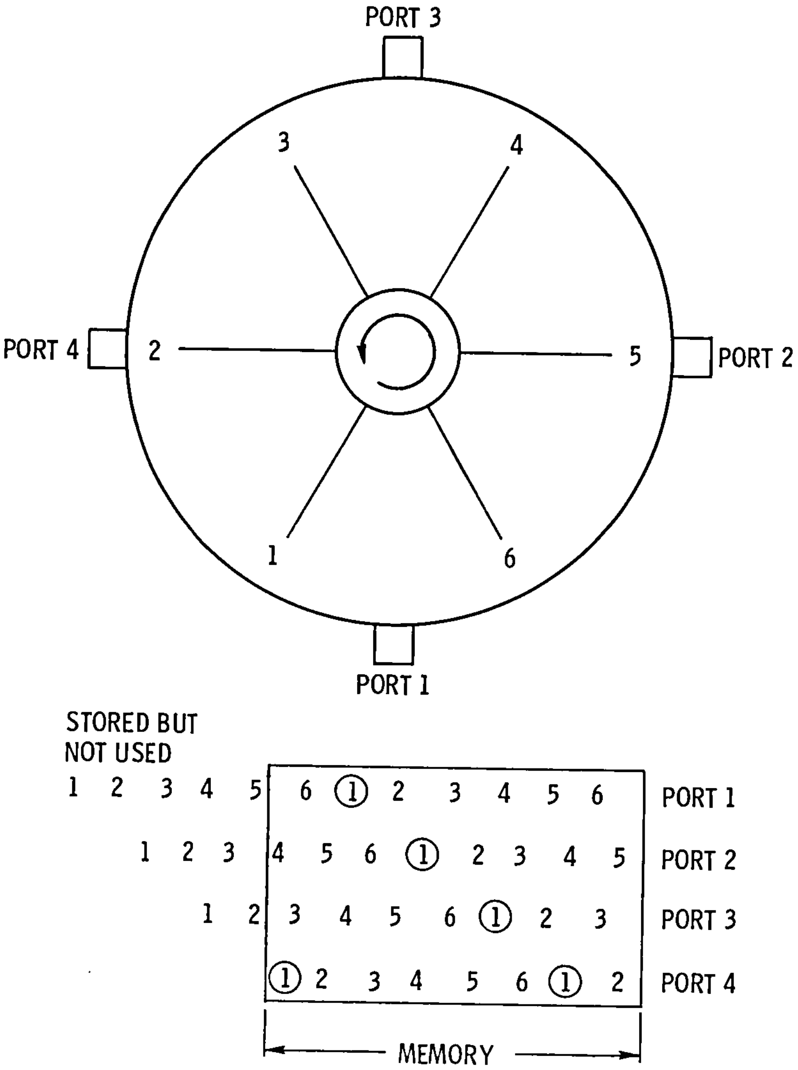


Figure 3. - Hypothetical six bladed rotor.

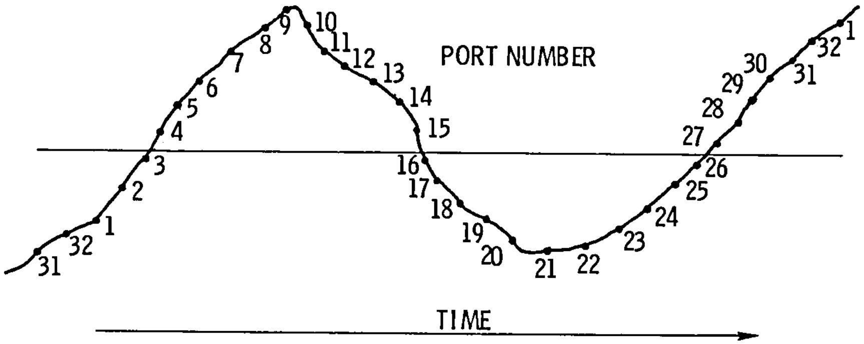


Figure 4. - Reconstructed time domain vibration signal.

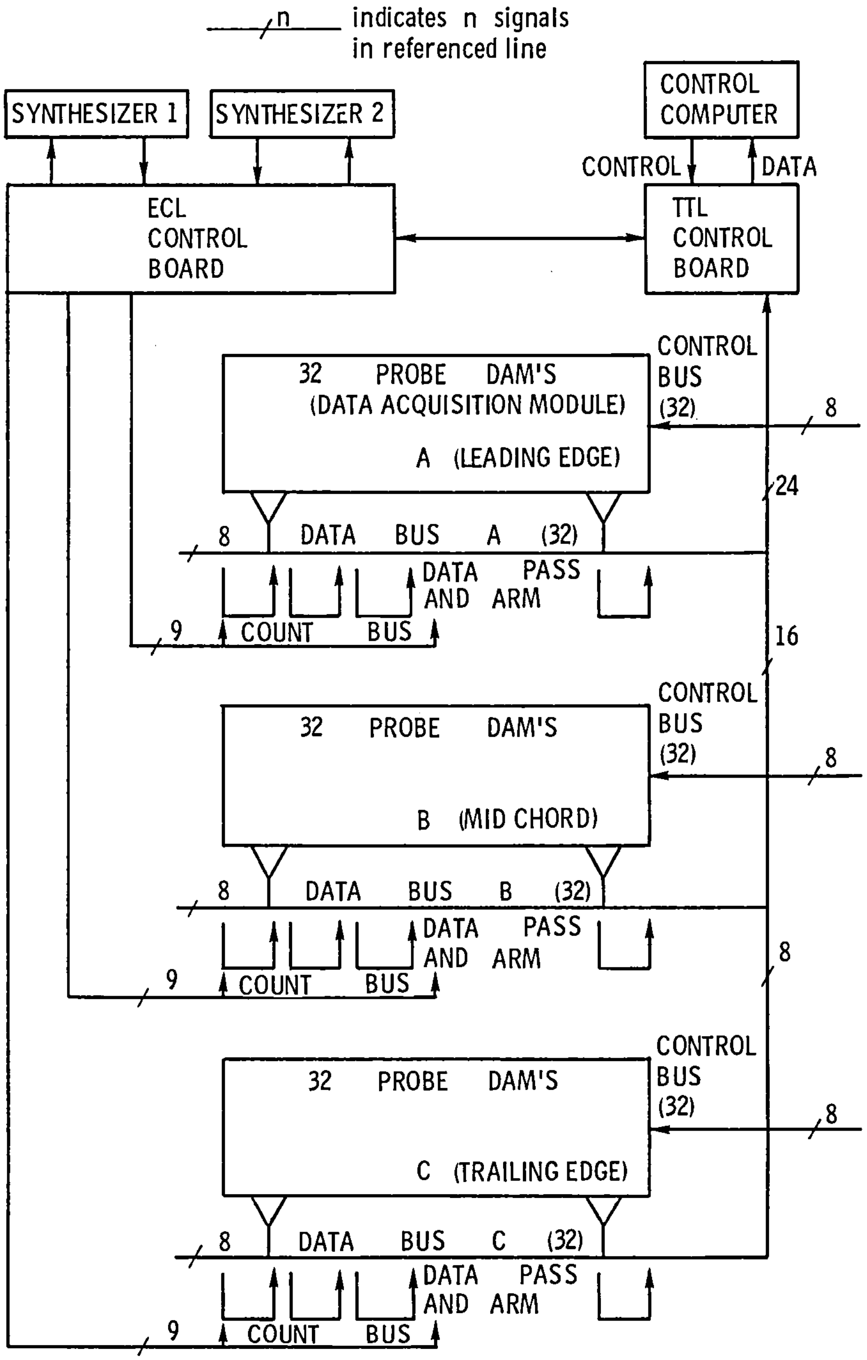


Figure 5. - System block diagram.

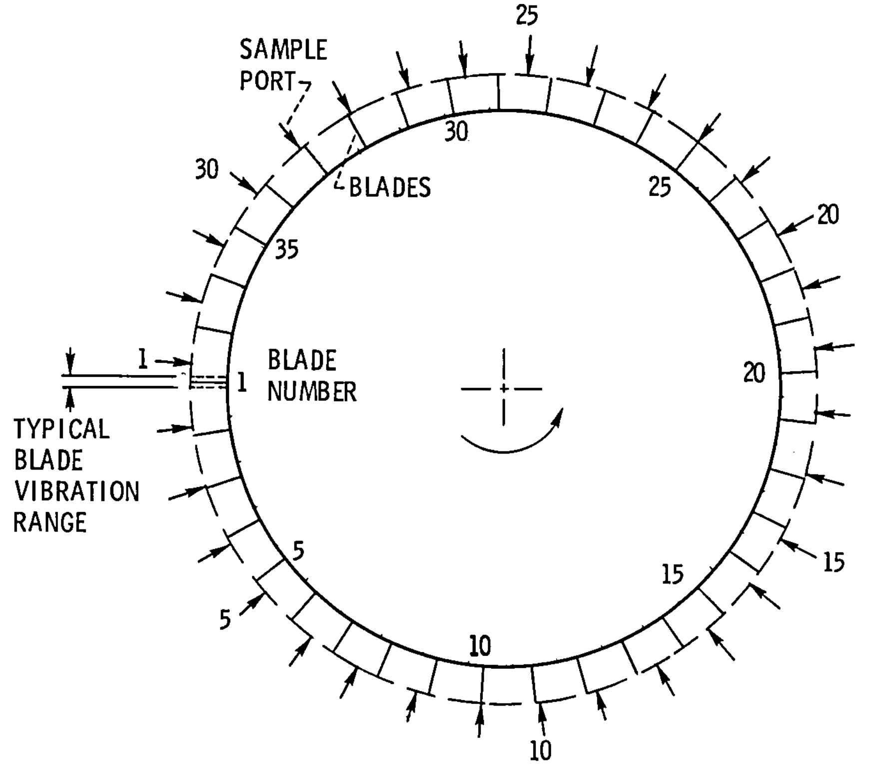
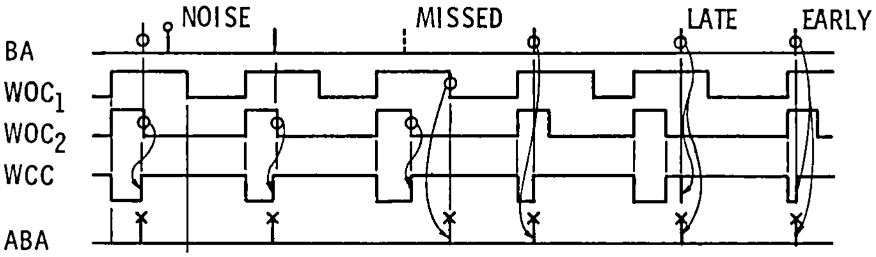
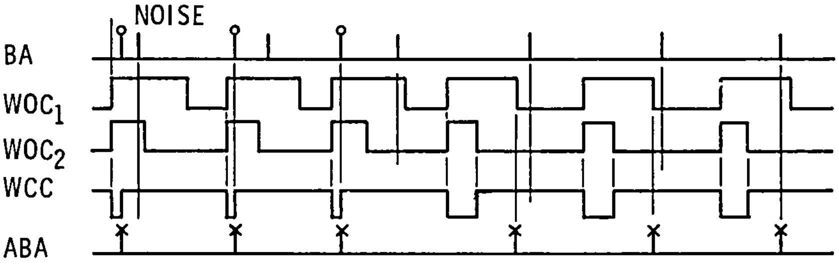


Figure 6. - 37 Bladed rotor with 32 sample ports schematic.



CASE 1 - BLADE PULSE MISSING



CASE 2 - EXTRA NOISE PULSES

Figure 7. - Operation of window counters.

DATA ACQUISITION MODULE BLOCK DIAGRAM (DAM)

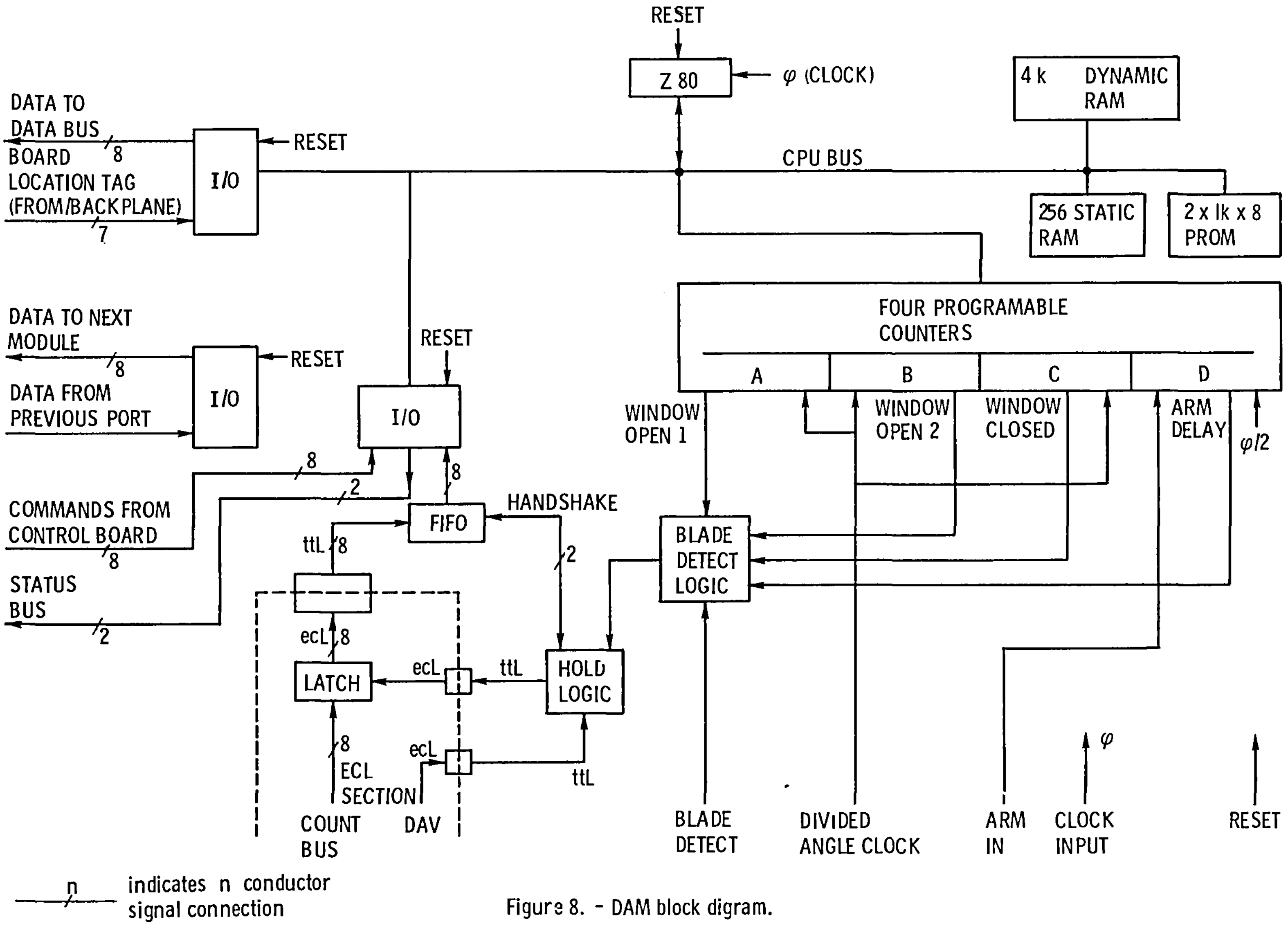


Figure 8. - DAM block digram.

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15. Supplementary Notes

16. Abstract

An instrumentation concept for measuring blade tip displacements which employs optical probes and an array of micro-computers is under development by the NASA-Lewis Research Center. The system represents a hitherto unknown instrumentation capability for the acquisition and direct digitization of deflection data concurrently from all of the blade tips of an operational engine rotor undergoing flutter or forced vibration. System measurements are made using optical transducers which are fixed to the case. Measurements made in this way are the equivalent of those obtained by placing three surface-normal displacement transducers at three positions on each blade of an operational rotor. The difficulties normally associated with strain gage life and durability can be reduced. The costs associated with the mounting of the strain gages and the installation and maintenance of slip rings can be minimized or avoided. The system reported herein directly digitizes a minimum of a 2048 point time-deflection history for each of the three measurement locations on each blade. For a 64-bladed rotor operating at 18000 RPM, 393216 data points are taken in a minimum sample period of 70 milliseconds. Alternate modes of operation can expand the sample period and/or acquire additional data from only selected subsets of the blading. Provisions within the design concept automatically correct the data points for rotor speed variations, nominal blade-to-blade and instrumentation probe misalignments, and either blade data points that are missed or extraneous blade data, generated by foreign objects passing the optical probes.

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