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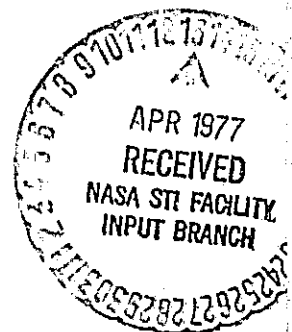
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OPTICAL DETECTION OF BLADE FLUTTER

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APR 1977
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W.C.Nieberding and J.L.Pollack

ABSTRACT

A joint Air Force-NASA flutter research program using full
scale turbine engines is being conducted at the NASA Lewis
Research Center. The initial phase is a fan flutter program
using a YF-100 turbo-fan engine. In these tests dynamic strain
gages mounted on rotor blades are being used as the primary
instrumentation for detecting the onset of flutter and defining
the vibratory mode and frequency. Optical devices however are
being evaluated for performing the same measurements as well as
providing supplementary information on the vibratory
characteristics. Two separate methods are being studied:
stroboscopic imagery of the blade tip and photoelectric scanning
of blade tip motion. Both methods give visual data in real time
as well as video tape records. The optical systems will be
described and representative results will be presented. The
potential of this instrumentation in flutter research will be
discussed.

INTRODUCTION

An investigation of two methods of optically detecting the
onset of flutter in the fan blades of an aircraft gas turbine
engine is reported herein. This investigation, conducted at the
NASA Lewis Research Center, is part of a joint NASA-Air Force

NASA Lewis Research Center
Cleveland, Ohio

program aimed at the expansion and strengthening of the technology base of aircraft gas turbine propulsion systems.

As an important part of this full scale engine research activity, a series of investigations is being conducted at Lewis on aeroelastic instabilities in compressor and fan blades. These instabilities, referred to as "flutter", need no external periodic forcing function. In this phenomenon a slight disturbance to the blade results in a continuous oscillation at one or more of the natural frequencies of the blade. In time, the amplitude of this oscillation can reach catastrophic proportions. Flutter is usually characterized by frequencies which are not integer multiples of the shaft rotational frequency.

To understand the flutter phenomenon, it is necessary to study both the blade structure and the aerodynamic system just prior to and at the onset of flutter. To obtain data for this purpose, it is necessary to drive the fan or compressor into flutter. This is a very dangerous maneuver because once flutter begins it can increase very rapidly in amplitude to catastrophic proportions; therefore, it is very important to reliably detect the slightest onset of flutter.

Reported experience with turbo-machinery flutter testing in this country has been limited. Host of the flutter instrumentation experience at Lewis and elsewhere has been with blade mounted strain gages used to indicate the dynamic strains

In the blade structure. The number of strain gages used is very large, normally 50 to 100 gages, because flutter can occur, depending on engine test conditions, on any blade and on any stage, without necessarily occurring on the other blades. This fact requires monitoring each gage signal separately and simultaneously.

Problems associated with strain gages used in these applications are:

1. The high cost of strain gage installation.

2. The extensive manpower and equipment requirements to monitor a large number of gages separately and simultaneously.

3. The high failure rate of strain gages.

4. The danger of not having an operating gage on a critical blade especially after numerous gage failures.

5. The unknown degree to which the gage alters the blade aerodynamic and/or mechanical performance due to its physical presence on the blade surface.

The investigation reported herein was undertaken in an attempt to find an alternative, less expensive, and simpler system. We also desired a monitor which demanded such minimum attention that the engine operator could observe and interpret it while performing his other critical functions.

Since real time monitoring of many blades in many stages is required, optical scanning techniques were considered. A recent

paper by H. Stargardter (ref. 1) reports the use of mirrors
mounted to a blade to measure deflection versus radius on a
fluttering fan blade. Limited optical access in our full scale
engine test made application of this technique impossible. In
addition Stargardter's method has problems analogous to 4 and 5
listed above for strain gages. We evaluated two other optical
techniques both of which sense only the tip deflection of all the
blades in a stage. These two tip monitoring techniques were
evaluated on a full scale engine. One was a vibration detection
method developed by Hohenberg (ref. 2) and used at Lycoming
Division of Avco Corporation in the 1960's. A variation is also
reported in the Russian literature (ref. 3). The second method
was the straightforward application of the familiar, time-tested,
stroboscopic technique.

Advantages of these optical devices are (1) they are
noncontacting and noninterfering, (2) they do not require
attachments to the rotating shafts and blades, and (3) the
display of the measurement can be in real time, readily
interpreted by engine operators and researchers. Evidence of this
ready interpretation is difficult to illustrate with the still
photographs presented in this paper, but it is dramatically
apparent when viewing either the real time display or the video
tape record. An additional advantage is that the optical
techniques, if proven reliable, could extend the test period
beyond the life of the strain gages.

The purpose of this paper is to describe these two different

optical techniques: Photoelectric Scanning (PES) and
Stroboscopic Imagery (SI). Both systems were installed on the
first stage of the YF-100 fan used in Lewis' current flutter
program. Both were in use simultaneously during flutter and the
results are compared. As presently implemented the two optical
systems present a TV type display which is most applicable as a
diagnostic and monitoring tool. Though the quantitative
information is in the video tape record, this type of record does
not lend itself to simple data reduction techniques. This paper
also presents the design concepts for a future system which not
only enhances the display characteristics but also produces a
readily processed digital data record.

OPTICAL MONITORING TECHNIQUES

Photoelectric Scanning System

As described in ref. 2 the basic PES method is to measure
the time at which a point on the tip of each blade passes a
sensor mounted in the fan housing. Figure 1 shows the
implementation of this system for the present investigation. If
the time between subsequent passings of the tip remains a
constant the blade is either vibration free or is vibrating at an
integer multiple of the once-per-revolution frequency. If the
time between subsequent passings of the tip is not constant then
blade flutter is present.

As explained in ref. 2 and in more detail later in this
report, the variations in time difference measurements for
certain pairs of sensor signals are proportional to blade torsion

and for other pairs are proportional to blade bending. More specifically, the data available from the PES can be reduced to give both torsion angle and the location of the torsion axis if only torsion is present. Alternatively, the data can be reduced to give bending amplitudes if only bending is present. If however, both torsion and bending are present simultaneously then ambiguities result if just two tip sensors are used. Correlation with other signals, such as those from strain gages, or prior knowledge of modes of vibration can remove some or all of the torsion versus bending ambiguity.

The PES signals provide a measure of the circumferential displacement of the sensed spots. Errors in this measurement are caused primarily by noise in the probe signals. The analysis which allows the calculation of the spatial errors caused by this noise is found in most electronic counter manuals. The result is that the spatial displacement error is equal to the product of tip speed and peak noise amplitude divided by the slope of the probe signal. Thus our probe system development efforts continually strive for minimum pulse rise time (maximum slope) and also minimum noise.

As shown in figure 1, two photomultipliers were used to detect light originating from a single light source and reflected from small viewed areas near the midchord and trailing edge of the passing blades. As the blades pass the optical port the two photomultipliers generate two trains of pulses. The corresponding pairs of pulses from each blade, or one of these

pulses and a corresponding once-per-blade shaft oriented pulse, are electronically compared to obtain their time difference. The change in this time difference is a measure of blade torsion or bending. The measurement is automatically repeated for all the blades in a stage once for each revolution of the shaft.

An existing 32 mm diameter port on the YF-100 fan casing that was directly over the first stage fan blades was used for optical access. A clear window was installed in the port. The blade tips of the first stage fan were coated with aluminum paint to increase reflectance. A rugged tungsten filament lamp, mounted in a water cooled holder, illuminated the passing blade tips. Two 6 mm diameter 13 mm focal length lenses, centerlines spaced 19 mm apart, were mounted in the same water cooled holder 15 mm from the blade tip. The lenses collected the reflected radiation from a .7 mm diameter field of view on the passing blade tip and imaged it onto two incoherent fiber optics bundles. The 3.7 meter long bundles passed through a bulkhead in the test facility enclosure and directed the reflected light to the photomultipliers. Variation of lamp and photomultiplier voltages was required to optimize signal-to-noise ratio. A typical display of the PES on a cathode ray tube is a vertical row of bright dots - one for each blade. Any blade deflection results in a time difference that is viewed as a dot displacement along the horizontal. Flutter produces a horizontal dot oscillation. The dot motion is due to blade torsion or bending depending on which pair of signals are selected as stated above.

The signal processing and display used to obtain the PES
data presented in this paper were basically like those of
Hohenberg (ref. 2). A block diagram is shown in Fig. 2.

Four signals were used in various combinations to obtain the
display on a standard oscilloscope. The signals are:

1. A pulse occurring once-per-revolution obtained when a
single tooth on the shaft passes a magnetic sensor.

2. A pulse occurring once-per-blade obtained as teeth on
the shaft equal in number to the number of blades pass
another magnetic sensor.

3. A pulse occurring once-per-blade obtained from a
photomultiplier as each blade passes the optic probe mounted
near the midchord position.

4. A pulse obtained the same way as 3 but from the optic
probe mounted near the trailing edge.

Thus, signals 1 and 2 are shaft oriented in time (i.e. their
phase remains fixed relative to the shaft, wheel, and blade
roots) while signals 3 and 4 are blade tip oriented in time.
Each of the four pulse signals was preconditioned by sending it
to an amplifier, comparator, and monostable multivibrator so that
all four signals were separate, short duration, TTL
(transistor-transistor-logic) compatible pulses.

As shown in fig. 2, signal 1 was used to reset a counter
once-per-revolution. The other three signals were used in
various combinations (as shown on the figure) to obtain a display

which showed either primarily the blade bending or the blade
torsion. The data shown in this report were all taken with
combination II.

With one of the once-per-blade signals applied to point A,
the signal applied to the oscilloscope Y axis was a staircase in
which each riser occurred at the time of a pulse at A and in
which the reset to zero occurred at the once-per-revolution pulse
time (see inset in Figure 2). The same signal (at A) was also
used to trigger the horizontal sweep. The combination of these
signals produced a raster progressing from the bottom to the top
of the screen with the same number of lines as blades. (The
blades were arbitrarily numbered beginning with one at the bottom
of the screen and increasing upward.)

Another once-per-blade pulse (selected according to the
chart in figure 2) was time delayed (with a variable monostable
multivibrator) to brighten the scope beam (Z axis). The time
delay was necessary in order to be able to set a high enough
sweep speed on the scope to obtain sufficient blade motion
resolution. The amount of delay depended on the absolute time
between the two pulses applied to points A and B. Since this
time depended on blade velocity which is proportional to RPM, it
had to be readjusted whenever significant changes in engine speed
occurred in order to bring the bright spots to approximately
center screen. This fact makes the absolute horizontal position
of the spots on the screen meaningless unless the time delay is
carefully measured and noted.

The spots do not line up vertically due to very slight steady state variations in the blade-to-blade spacing relative to the tooth-to-tooth spacing for combinations I and II. Also in combination III vertical lineup is affected by very slight variations in steady state blade angle.

Even though absolute position of the spot on the screen is meaningless without accurate knowledge of time delay, a steady state shift in the spot position is meaningful if the time delay is not changed. This steady state shift is proportional to steady state torsion or bending or to exact engine order vibration amplitude in torsion or bending.

Any periodic variation in the position of the intensified spot on the horizontal sweep in combination I is due to blade bending in flutter. In combinations II and III this cyclical variation is due to torsion in flutter. The magnitude of the blade deflection is proportional to the deflection of the intensified spot on the horizontal sweep line.

The system in figure 2 was completed with a TV camera and video tape recorder photographing and recording the scope display. Photos presented in this report were taken from the videotaped record.

Stroboscopic Imagery

As mentioned in the introduction, the SI method is a straightforward application of a familiar time-tested stroboscopic

technique. In our system (fig. 3), any preselected blade tip may
have its apparent motion arrested by a short duration light pulse
as the blade passes before a viewing window. If the signal which
triggers the electronic flash lamp is shaft oriented in time
(i.e. is derived from shaft position as opposed to blade tip
position) then any apparent vibratory motion in the otherwise
frozen blade image is flutter.

The method was applied by using another 32 mm diameter port
in the first stage casing of the YF-100 fan. The port was
modified to accommodate a 30 mm diameter reticle-window on which
was ruled a 4 mm square grid. Through this window two 12 mm
diameter, 0.6 numerical aperture glass fiber light pipes
illuminated the blade tip. The 3.7 meter long light pipes
extended through a bulkhead in the test facility to the flash
lamp and its power supply located in a non-hazard area. The
xenon flash tube equipped with a special gas cooled sleeve was
capable of being pulsed at 150 pulses/sec for several minutes.
Energy per flash was .32 watt-seconds. Flash duration was
sufficiently short such that there was no visually detectable
difference in blade tip suction edge image sharpness between a
stationary blade and a corresponding blade obtained at operating
RPM with no flutter.

The recording system consisted of a photographic objective
lens (50 mm focal length, f/1.4) which viewed the trailing half
of the blade tip through the same ruled window used for
illumination. The lens to blade tip distance was 30 cm. The

lens imaged the blade tip onto a coherent optical fiber bundle.
The optical fiber bundle, 2.4 meters in length, passed through
the bulkhead where it was coupled to a closed circuit TV camera.
The camera signal was sent to a monitor for real time display and
to a video tape recorder. All components were obtained from
commercial sources.

This technique has all the advantages of photography. It
provides a high spatial resolution record which allows real-time
detection of small blade tip movement as well as allowing
measurement of blade tip position changes from the video tape
record.

The signal processing and display used to obtain the SI data
is shown in figure 4. Signals 1 and 2 of fig. 2 were also used
for this system. In order to be able to select any desired blade
for viewing, a preset counter which can be programmed to a preset
number (blade number in this case) was used. Signal 1 was used
to preset the blade number into the counter which then counted
down signal 2 pulses until a zero count was reached at which time
a trigger pulse issued forth from the counter. This pulse,
delayed by a variable amount of time, then triggered the flash
lamp to illuminate the selected blade.

As in the PES system, the variable time delay following the
preset counter output pulse was necessary to bring the blade into
view at nearly center screen on the monitor. The same situation
with regard to absolute position and steady-state position shifts

on this monitor apply as stated in the section on the PES.

RESULTS

The blade movements that appear on both the photoelectric
scanning (PES) and stroboscopic imagery (SI) monitors exhibit a
stroboscopic effect since the blade motion is being sampled at a
once-per-revolution rate. The observed blade movements that
appear on the monitor have an apparent vibration frequency that
is the difference between the actual blade vibration frequency
and the nearest integer multiple of the shaft rotational
frequency. Blade frequencies near an engine order exhibit the
familiar low-frequency "beating" effect. The motion associated
with large frequency differences was too rapid to be followed by
the eye.

Photoelectric Scanning

Figures 5 and 6 are photographs of the video tape record of
the oscilliscope screen taken using combination 11 (fig. 2)
before and during a flutter condition. As indicated on the
pictures, the horizontal sweep speed of the oscilliscope is 5
microsec/cm and the major vertical grid lines are 1 cm apart.
During quiet engine operation average jitter was carefully
measured by increasing the horizontal sweep rate and measuring
the variation in length of the brightening pulse. Average jitter
was 1/2 microsecond corresponding to 1/4 degree peak-to-peak
amplitude in the first torsional mode deflection of the blade
tip. During flutter, individual blades exhibited vibratory
peak-to-peak amplitudes ranging from 0.5 degrees to 7.5 degrees.

This measurement was made for each blade by subtracting the quiet engine pulse width of figure 5 from the corresponding expanded pulse width of figure 6 caused by flutter. Both photographs were 5 second exposures of the video tape record. Therefore both the apparent low and high frequency motions of the different blades (mentioned above in the stroboscopic effect disscussion) were measured.

A single photograph such as figure 6 does not do justice to the impact of the real time display for monitoring flutter nor to the advantage of more leisurely replay of the video tape record of flutter conditions. Each blade exhibits an individual behavior, which at this time is unpredictable. For instance, figure 6 shows that, at this particular condition, there are two groups of blades exhibiting larger amplitude than the others (blades 5 to 8 and 23 to 26 as counted up from the bottom) and that these groups are approximately 180 degrees apart circumferentially since there are 38 blades in this stage. In addition, we observed during operation that these two groups always went into flutter earlier and came out later than the other blades. These are observations that would not necessarily be noticed in most strain gage monitoring systems. The PES record clearly emphasized the requirement to monitor and record the deflections of all the blades and all the blade rows of interest.

Stroboscopic Imagery

The SI system produced a steady sharp television picture of

the trailing half of the blade during quiet engine operation.
Fig. 7 is a typical photograph obtained from the TV monitor
during quiet engine operation. Since at least four images are
superimposed during this TV frame, the photograph illustrates the
sharpness of the blade image during such a time.

During flutter, stepping along the blade row (using the
preset counter) produced dramatic video-tape records of all the
vibrating blades. Some blades were almost stationary, some had
large amplitude, up to 4.5 degrees. The blade motions varied
from an apparent frequency so high as to blur on the TV record
for some flutter conditions to as low as several hertz for
others. Using standard photogrammetry, measurements were made on
photographs produced from the video tapes. The change in angle
between the blade chord and the engine axis caused by change in
engine conditions was measured. Also, attempts were made to
measure blade uncamber. Within the 1/4 degree precision
determined for the SI system, no uncamber was detected.
Measurements from the same records have the potential to detect
higher order modes of torsional vibration, if present with
sufficient amplitude, and can serve as a guide toward reduction
techniques for the PES data.

DISCUSSION OF RESULTS

The video tape records of PES and SI at the same flutter
condition were compared over the same time interval. Amplitude
of vibration and apparent frequency agreed to within the
precision of the measurement for blades simultaneously monitored

by both systems. The fact that the maximum amplitude recorded by
the PES was 7.5 degrees and that recorded by the SI was 4.5
degrees results from the difficulty of selecting the right blade
at the right time with the SI system while the PES views all the
blades all the time. By the time the PES and SI systems were
implemented only three workable strain gages remained to compare
with the video records. This comparison was hampered by:

1. The lack of accurate time correlation between the strain
gage and optical systems. Emphasis to date has been on
developing a successful flutter monitor as opposed to a
flutter measuring system. As a result little effort was
expended in time correlating the systems.

2. The subjective judgment necessary to reduce visual
images from the video screen to quantitive data.

However, satisfactory qualitative correlation was achieved
between the optical and strain gage systems. Whenever either
optical system indicated flutter on those blades with strain
gages remaining it was confirmed immediately by the strain gage
system.

A problem exhibited by the present design of the optical
system is the previously discussed variation of the display
position with RPM caused by fixed time delays. Additionally,
since both PES and SI require optical access (windows) to the
blade tips, we were initially troubled by dirt on the windows
deteriorating the signal-to-noise ratio. The window design
described in this report resulted from attempts to eliminate this

problem and did perform satisfactorily.

In spite of the above difficulties the existing system has successfully demonstrated that (1) pulses of sufficient signal-to-noise ratio and time repeatability were obtained from the PES probes and shaft oriented sensors to obtain the 1/4 degree precision on torsion angle, and (2) these signals combined with the signal processing produced excellent flutter monitors for the YF-100 fan. Of particular value is to be able to view the behavior of all blades simultaneously.

POTENTIAL IMPROVEMENTS TO THE SYSTEM

Improvements are presently being incorporated to eliminate some of the remaining problems. These improvements will:

1. Eliminate the dependence on RPM of the absolute position of the signals on both the PES and SI display.

2. Produce digital data tapes of the parameters inherently available from the PES system for off-line quantitative data reduction correlated with time and thereby with other pertinent measurement systems.

The heart of the improved system is a scheme first suggested by J.A. Powell of the Lewis Research Center. It consists of generating a constant large number of very uniformly spaced pulses-per-shaft-revolution so that each pulse represents a given circumferential angle increment. (About 10,000 pulses-per-revolution are being used in our system). This device (which will be referred to as an angle clock) is illustrated in

block diagram form in Fig. 8. As can be seen from the figure, the microprocessor updates the frequency of the synthesizer each revolution based on the deviation of the counter counts-per-revolution from the desired counts-per-revolution. The assumption is that RPM changes are negligible during one revolution at engine conditions of interest which are at nominally constant RPM. In addition to having the angle clock signal available at the output of the synthesizer, a parallel digital representation of absolute angle is available at the counter output at all times.

It can be seen that this angle clock is really an electronic replacement for a rotary encoder since its function is to generate a large number of very uniformly spaced pulses-per-revolution. One of its advantages is that it can be applied in machinery where physical limitations such as available space or high shaft speed preclude the installation of an actual rotary encoder. Another advantage is that any integer number of pulses-per-revolution can be generated and this number is readily changed via software. In addition, in practice the microprocessor is functioning during only a very small fraction of each revolution so that it is then available during most of the time to do other useful things such as display control.

Two requirements for the angle clock are that a once-per-revolution pulse be available and that RPM changes be negligible during one revolution at times of interest. Another requirement is that the synthesizer must exhibit very rapid

settling time.

Processing and Recording

Figure 9 is a block diagram of the improved data processing
and recording system for the PES. The primary goal of this
system is to produce a digital data tape containing a number
proportional to the difference in circumferential angle between a
reference once-per-blade pulse and the once-per-blade pulse
derived from the appropriate photomultiplier. There will be one
of these numbers recorded for each blade passage of the midchord
photomultiplier and another for each blade passage of the
trailing edge photomultiplier for as long as the tape is running.
Also recorded with each pair (midchord and trailing edge) will be
the corresponding blade number. Time and RPII will also be
recorded to facilitate correlation with other data. Secondary
purposes of this system are to produce processed digital signals
for on-line display and to produce properly phased
synchronization pulses for the SI system and other systems
requiring synchronization signals.

The functions of the components in figure 9 are to produce
the requisite signals. The function of the preset counters is to
produce pulses optimally angularly spaced (or phased) relative to
each other for the rest of the system. This is necessary in
order to allow for the arbitrary angular location of the
once-per-revolution pulse and the PES sensors as well as for the
initial mechanical variations in blade spacing. The function of
the digital frequency divider is to provide the once-per-blade

shaft oriented pulse formerly derived from the toothed wheel on
the shaft, but now derived from the angle clock. The advantage
of this approach is that the resultant pulse spacing is not
dependent on machining tolerances of the teeth and thus is more
uniform as a reference signal. Its use assumes that the selected
number of pulses-per-revolution from the angle clock is an
integer multiple of the number of blades. The start-stop
counters count angle clock pulses between selected pairs of
pulses and present the digital results to the tape recorder.
These digital signals are the primary data. They exhibit a
resolution equal to the selected angle clock pulse resolution.
The blade counter provides the blade number to the tape for
identification.

<div align="center">Display</div>

Figure 10 shows the PES display system for real-time
monitoring. The microprocessor (same one as in figure 8)
initially calculates a table of offset numbers for each
photomultiplier derived pulse for each blade when the engine is
in a quiescent (not fluttering) running state. The offset is
based on the number necessary to place each bright spot at
horizontal center screen during this reference condition. From
then on the microprocessor subtracts this previously calculated
offset from the corresponding data entry to produce the
horizontal position number. Each horizontal position number
output is converted to an analog signal for the X axis drive of
the display. The microprocessor then pulses the Z axis to

brighten the beam. At all times the digital blade number is also being converted to an analog voltage to drive the Y axis so that the beam is always in the correct vertical position to receive the X and Z signals.

This scheme no longer requires oscilloscopes for display but rather X-Y-Z cathode ray tube displays. It also now permits direct interpretation of both absolute and relative beam positions because they are all relative to the original, fixed, known reference position calculated by the microprocessor.

Since all of the delays are digitally determined, based on the angle clock, the beam position is no longer a function of RPH. This allows the various digital delays to be set once for each engine mechanical configuration and then never changed.

The SI display system is shown in Figure 11. The digital delay features are the same as for the PES system. Thus, the selected blade is readily positioned on the screen and its position is not a function of RPH. All changes in position are now interpretable. It can be seen that systems similar to the SI display system can readily be adapted to provide synchronization to other systems with similar requirements.

CONCLUDING DISCUSSION

The photoelectric scanning system (PES) is the simpler, and more easily operated, of the two optical systems. Since a single cathode ray tube displays the behavior of all the blades in a stage simultaneously, it is an ideal flutter monitor. When an

engine operator maneuvers into the flutter condition he can tell at a glance how changes in engine operating parameters affect the degree of flutter. With the addition of the system improvements described, but not yet implemented, the PES ought to provide a complete quantitative capability to obtain tip amplitude, and relative phase of all the blades.

The stroboscopic imagery system (SI) provides higher chordwise spatial resolution and less ambiguous records from which higher precision measurements of blade uncamber, first torsion, and higher order torsion may be detected. Operation of the SI system continuously while searching for a flutter condition imposes severe demands on the flash tube and affects its reliability. This limits its use as a flutter monitor. Experience has shown that a better method of operation is to search for flutter with the PES and limit the use of SI to those times during which the PES indicates interesting blade activity. Using the two optical techniques to complement one another produces two separate measurements of tip motion and a corresponding high level of confidence in the results.

Both systems require optical access (windows) for operation. Dirt from the inlet air piping carried into the fan can be a problem. Experience showed that the SI performance is less affected than the PES performance by deposits on the window. Deposits did adversely affect the signal-to-noise ratio on the PES.

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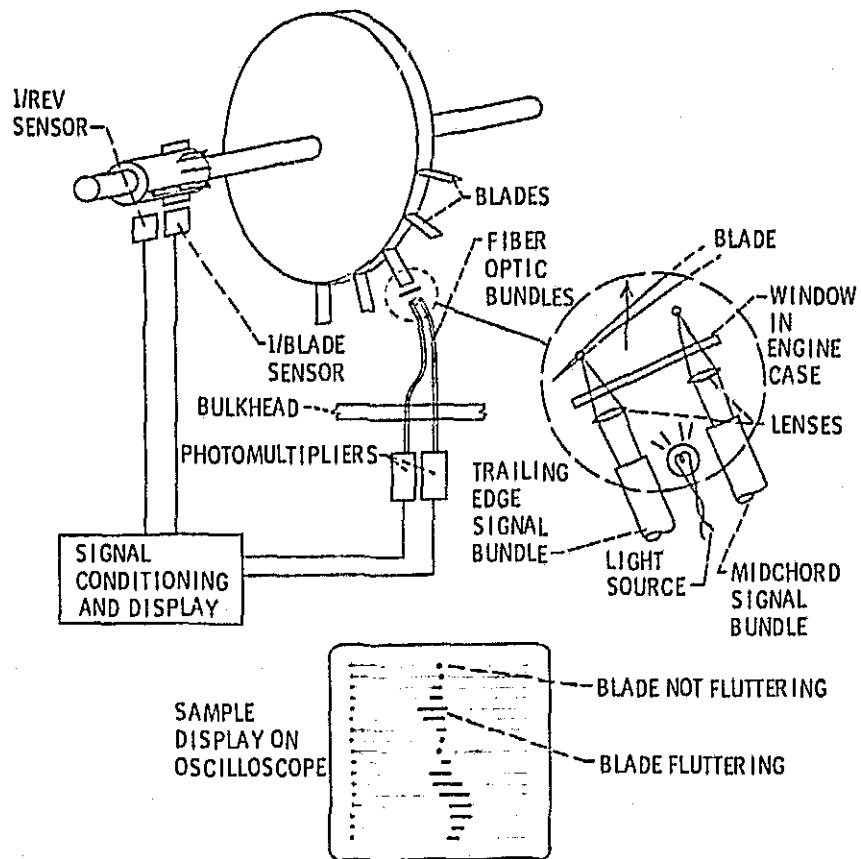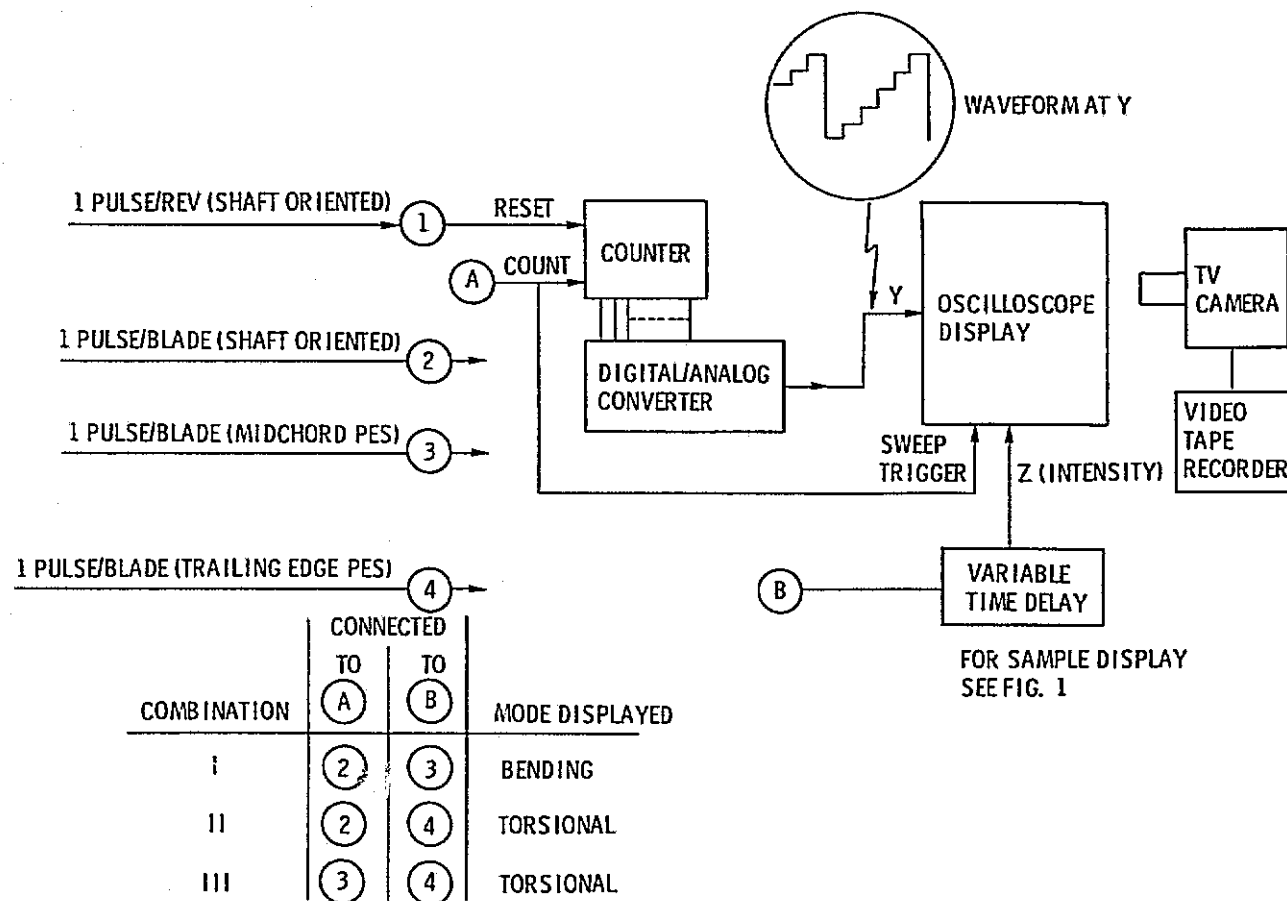
Figure 1. – Photoelectric scanning system (PES) elements.

WAVEFORM AT Y

1 PULSE/REV (SHAFT ORIENTED) ──▶ (1) ──RESET──▶ COUNTER

(A) ──COUNT──▶

1 PULSE/BLADE (SHAFT ORIENTED) ──▶ (2) ──▶

1 PULSE/BLADE (MIDCHORD PES) ──▶ (3) ──▶

DIGITAL/ANALOG CONVERTER

Y

OSCILLOSCOPE DISPLAY

TV CAMERA

VIDEO TAPE RECORDER

SWEEP TRIGGER   Z (INTENSITY)

1 PULSE/BLADE (TRAILING EDGE PES) ──▶ (4) ──▶

(B) ──── VARIABLE TIME DELAY

FOR SAMPLE DISPLAY SEE FIG. 1

| COMBINATION | CONNECTED | | MODE DISPLAYED |
	TO (A)	TO (B)	
I	(2)	(3)	BENDING
II	(2)	(4)	TORSIONAL
III	(3)	(4)	TORSIONAL

Figure 2. – Block diagram of PES signal conditioning and display.
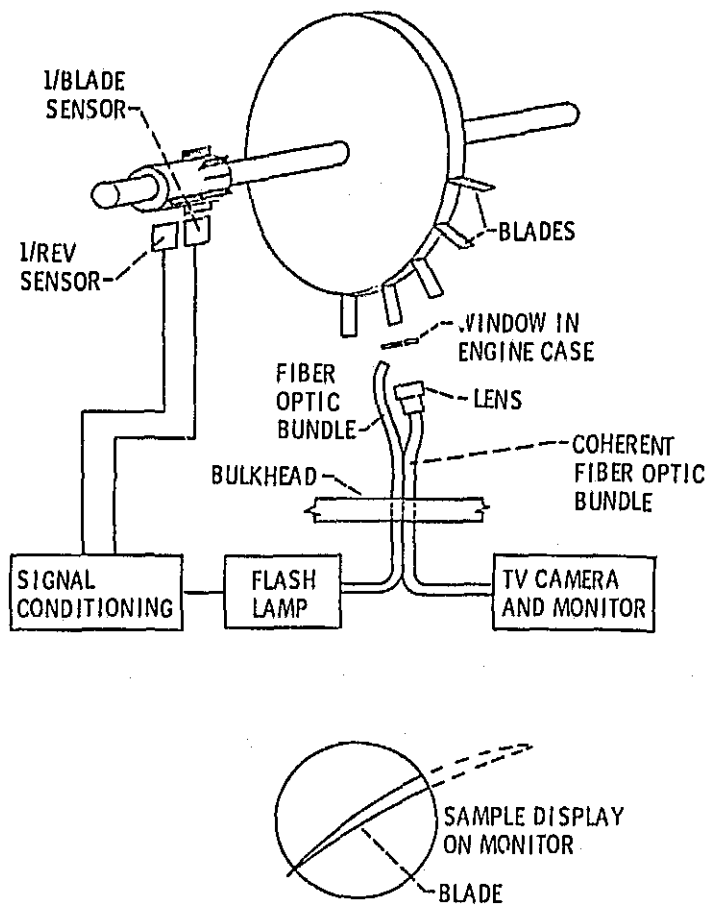
Figure 3. - Stroboscopic imagery system (SI) elements.
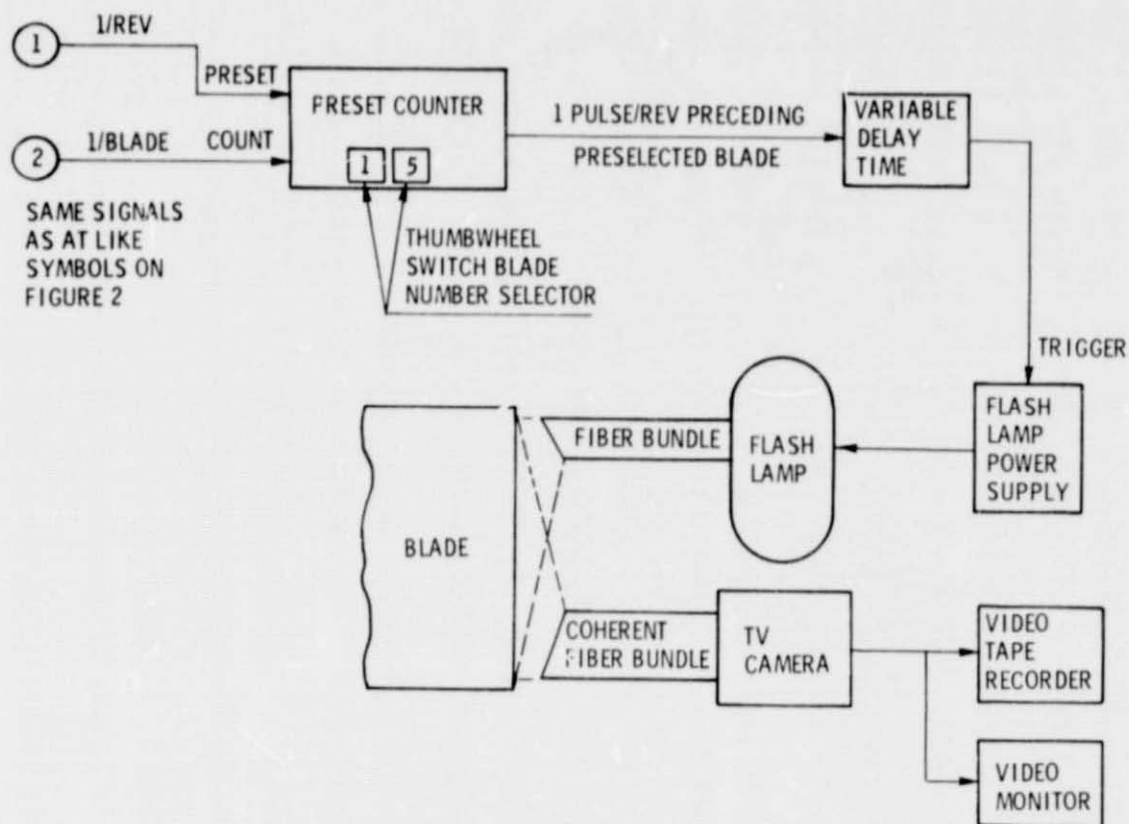
Figure 4. - Block diagram of SI signal conditioning and display.
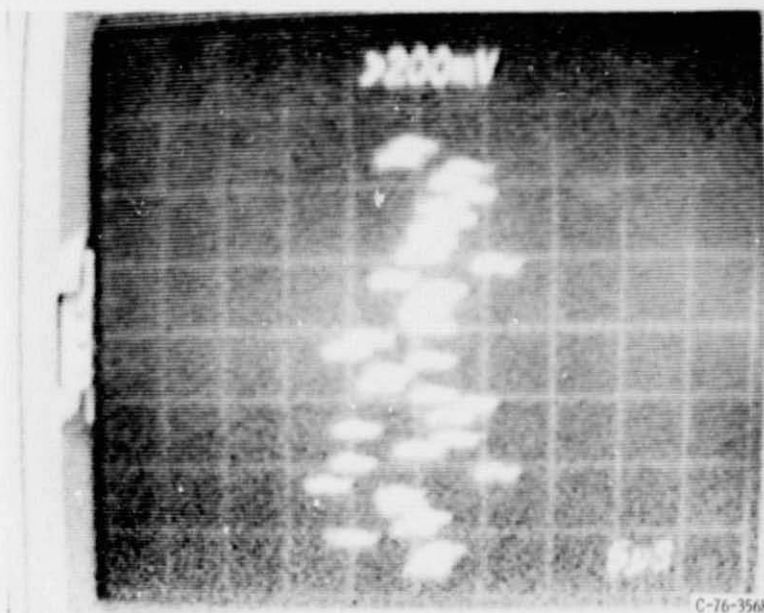
Figure 5. - PES display during quiet running condition
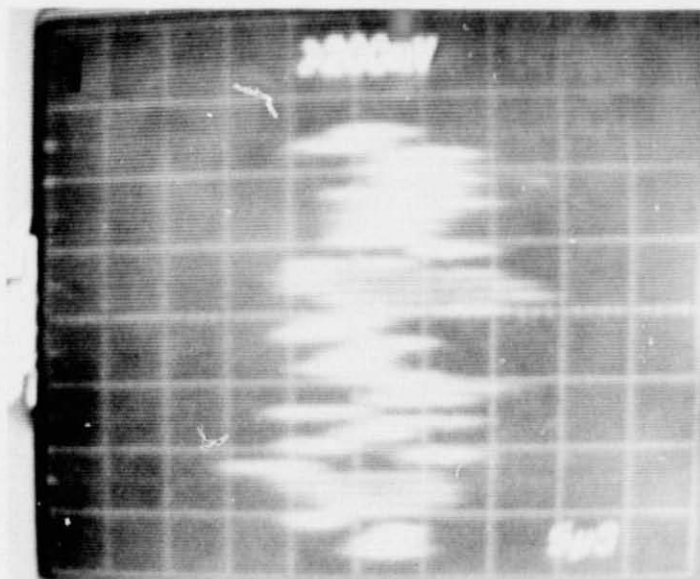
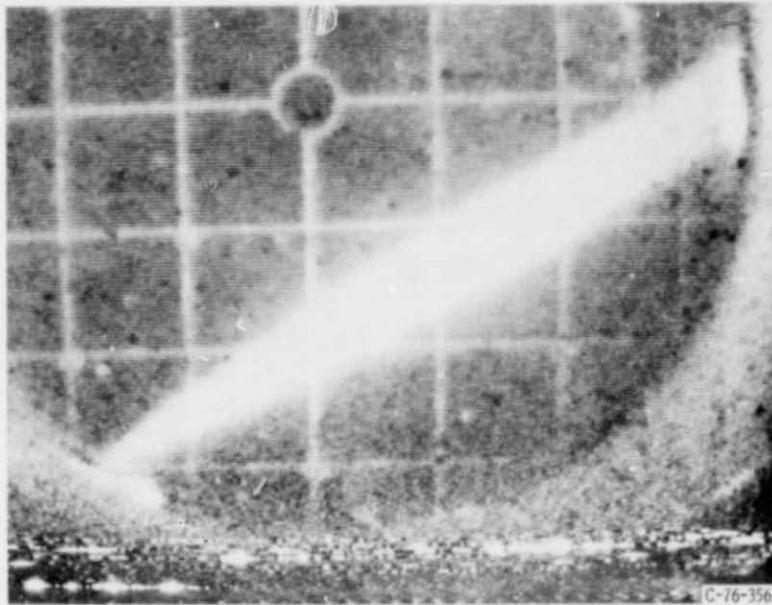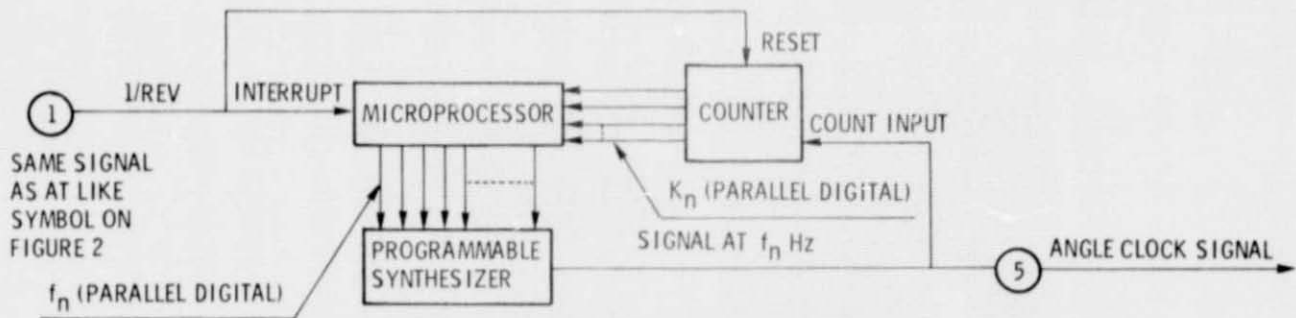Figure 6. - PES display during flutter

Figure 7. - SI display of blade image during quiet running condition

$$f_n = f_{n-1} \frac{K_o}{K_n}$$

WHERE:

$K_o \equiv$ DESIRED PULSES PER REVOLUTION
$K_n \equiv$ ACTUAL PULSES PER REVOLUTION
$f_n \equiv$ FREQUENCY NECESSARY TO ACHIEVE K_o
$f_{n-1} \equiv$ FREQUENCY SENT TO SYNTHESIZER
ON PREVIOUS REVOLUTION

Figure 8. - Block diagram of angle clock system.
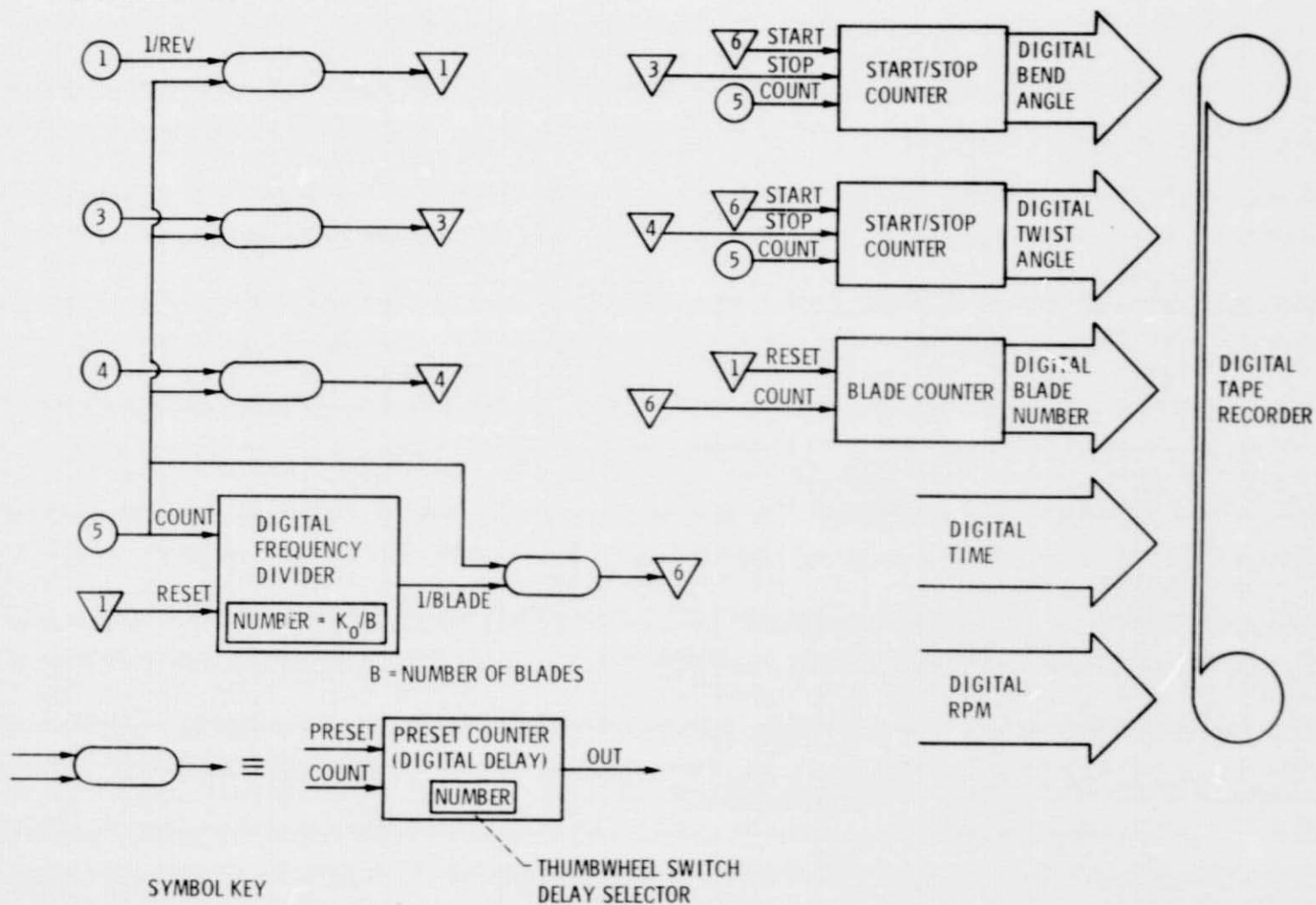
Figure 9. - Block diagram of improved PES signal processing and recording.
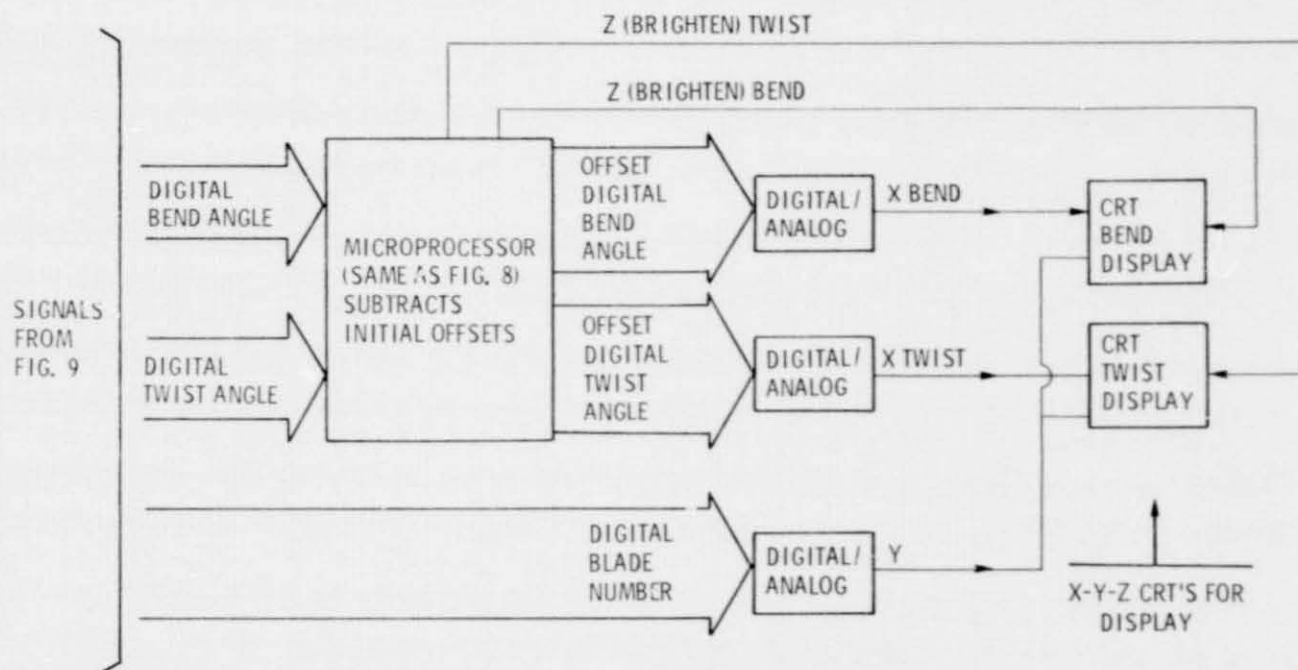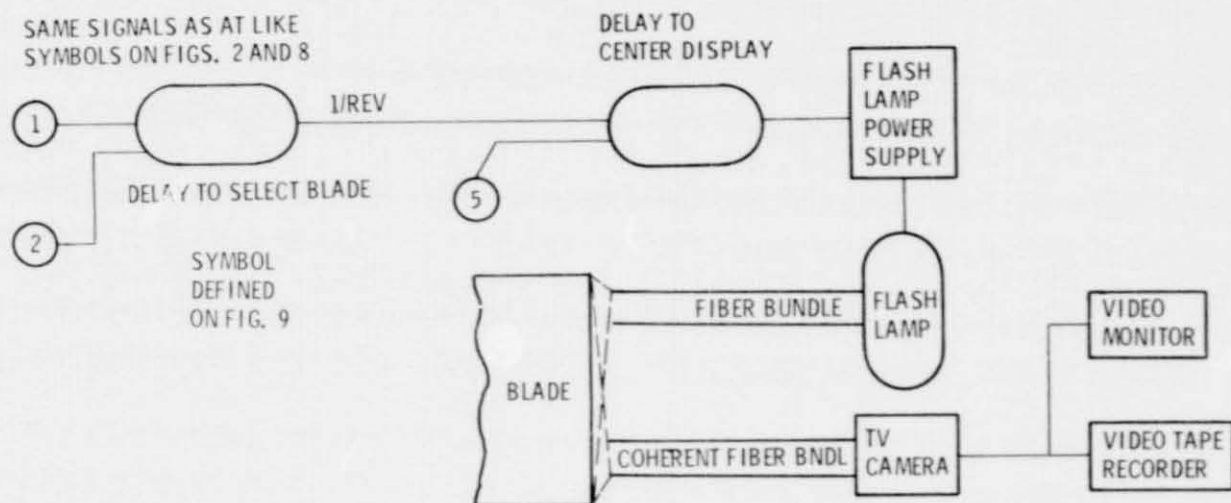
Figure 10. - Block diagram of improved PES display.

Figure 11. - Block diagram of improved SI signal conditioning and display.