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MICROPROCESSOR-BASED MULTICHANNEL FLUTTER MONITOR USING DYNAMIC STRAIN GAGE SIGNALS

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ABSTRACT

Two microprocessor-based multichannel monitors are described for monitoring strain gage signals during aerodynamic instability (flutter) testing in production type turbojet engines. One system monitors strain gage signals in the time domain and gives an output indication whenever the signal amplitude of any gage exceeds a pre-set alarm or abort level for that particular gage. The second system monitors the strain gage signals in the frequency domain and therefore is able to use both the amplitude and frequency information. Thus, an alarm signal is given whenever the spectral content of the strain gage signal exceeds, at any point, its corresponding amplitude vs. frequency limit profile. Each system design is described with details on design trade-offs, hardware, software, and operating experience.

INTRODUCTION

NASA Lewis Research Center has implemented a long-range, full-scale engine research activity aimed at the expansion and strengthening of the technology base of aircraft gas turbine propulsion systems. The overall program approach is to select for investigation those problem areas where there is incomplete comprehension of phenomena and interactions governing the internal aerodynamic, thermal, and structural behavior of gas turbine engines under a variety of operating conditions. The emphasis is directed toward the generation of information applicable to the design of future engines so that problems can be avoided and/or performance improved.

The first problem area to be investigated is a special type blade vibration called "flutter." Vibration of turbojet engine compressor and turbine blades results in a variety of consequences ranging from nuisance types to those of an extremely serious nature. Severe vibration can result in extremely high stresses necessitating immediate engine shutdown in order to prevent damage to the engine. While occurrences of this nature are not frequent, there is documentation of single engine aircraft being lost due to cases of severe blade vibration. A more common occurrence in engine operation is a low or moderate amplitude vibration over a long time period. This can shorten the useful life of either compressor or turbine blades to the point where the blades must be replaced periodically to avoid fatigue failure.

The cases and types of vibrations in compressor and turbine blades are numerous. Some vibrations can be eliminated completely once the nature and cause is understood, while others are an inevitable by-product of engine operation, and at best can only be minimized. In general, compressor and turbine blade vibrations fall into two categories:

1. Forced vibrations - dependent on and governed by the characteristics of an external alternating energy source usually called a "forcing function."
2. Aeroelastic vibration (called flutter) - self-excited, self-governed and dependent only on the motion of the blades and the prevailing aerodynamic conditions.

The excitation source in the case of forced vibrations is some forcing function within the engine usually generated by disturbing the air flow so that the blade load is periodically varied. Examples of this are inlet distortion and air blockage by struts or stator vanes. Faulty bearings, gearing, or unbalanced components can develop periodic loads and thereby cause vibrations. Forced vibrations are characterized by integer order excitations, which means that the vibrating frequency is some whole number times engine speed. This is not true for "flutter."

Aeroelastic vibration, referred to as flutter, needs no external forcing function. In this phenomenon, a slight disturbance to the blade results in a continuous oscillation, at one or more of the resonant frequencies of this blade, which can reach catastrophic proportions.

As shown in Fig. 1, the "flutter" vibration is dependent on the interaction of the blade structure and aerodynamic forces which act on the blade. When the phase relationship between these is such that they reinforce one another, the flutter will begin and will grow until some limit is reached.

To understand the flutter phenomena, 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 operate a turbojet engine at test conditions prior to, and at the onset of flutter. This is a very dangerous maneuver because once flutter begins it can increase very rapidly to catastrophic proportion. Therefore, it is very important to detect the slightest onset of flutter.

As shown in Fig. 2, the normal technique for performing flutter investigation tests is to use blade mounted strain gages as the indication of the dynamic forces in the blade structure. The number of strain gages used in very large, normally 50 to 100 gages, because flutter can occur, depending on engine test conditions, on any blade and on any rotor, without necessarily occurring on the other blades. These strain gage signals are transferred from the rotating shafts, usually by the use of slip rings, to conventional strain gage signal conditioners. After conditioning, the signals are recorded by a FM tape recorder system for research analysis after the test is over. These signals are also displayed on a bank of oscilloscopes, one scope for each gage. During the test, it is the task of two or three research engineers to constantly monitor these oscilloscopes for the slightest indication of the flutter phenomena.

The purpose of this paper is to describe two microprocessor based multichannel flutter monitors which were designed at the Lewis Research Center to improve the monitor accuracy and to eventually replace the bank of oscilloscopes. The general requirements for a monitor system are:

1. It should be quasi real time - (1 to 2 second response).
2. It should reliably detect flutter.
3. It should monitor all critical strain gages.
4. It should alarm test personnel as to which gage indicates flutter and the amplitude of the flutter.
5. It should take into account the fact that the signal which indicates flutter may be different for each gage. (Level and/or frequency)
6. It should be sufficiently flexible so that as more knowledge of flutter is gained, the monitor can be readily changed to account for different gaging schemes, different limit setting criteria, etc.
7. It should be as low cost and operating manpower efficient as possible.

TIME DOMAIN SYSTEM

The first microprocessor flutter monitor was designed to meet these requirements by monitoring the amplitude of the strain gage signals in the time domain.

Design requirements were:

1. To monitor 96 different strain gages installed on an engine rotor.
2. Compare the peak amplitude of each gage signal to two limits unique to each gage (called alarm and abort).
3. Make this comparison at a rate such that all gages are checked at least once a second.
4. To indicate by visual and audio means the out-of-limit condition and to display gage identification.
5. To automatically sense faulty strain gages and to mark any resulting signals which might be falsely interpreted as out-of-limit condition signals.
6. Provide an electronics system which does not contribute more than 1 percent error from 300 Hz to 10 kHz.
7. To use a 100 conductor slip ring to transfer the signals from the rotating shaft.
8. To use commercially available equipment or modules when possible.

Design Trade-Offs

To accomplish the design requirement, it was necessary to make certain design trade-offs. To minimize the system hardware it was decided to use one peak detector circuit and time multiplex the signals, rather than use a peak detector on each of the 96 gages. To meet the requirement that all 96 channels are monitored at least once a second, the peak detector can monitor a single gage for 1/96 of a second or about 10 milliseconds during every 1 second scan. This is not a serious constraint on the system because the flutter phenomenon can be considered stationary for a time period of a few seconds. However, the detection of a peak value of flutter using a window or aperature time of 10 milliseconds does limit the low frequency response. Allowing for two or three cycles of the lowest frequency flutter signal in order for the detector to obtain the peak value (within about 1% accuracy) results in a low frequency response of about 300 Hz. Since flutter can only occur at frequencies near the natural harmonic frequencies of the blade structure, this low frequency cut-off was acceptable for our tests. This peak detector aperature does, however, prevent the use of a much faster scan rate.

The requirement that the system monitor 96 rotating strain gages, using a slip ring of only 100 conductors to transfer the signals from the rotating shaft is a serious design constraint. To make efficient use of the number of conductors, strain gage wiring as shown in Fig. 3 is used. Each gage has its own constant current regulator for power excitation and uses a separate ring for one side of the gage. The other side of the gage is wired in common for all gages. Since the noise generated by a slip ring is proportional to the current carried by the ring, it is desirable to separate the power return ring from the signal return ring. Two rings are used for each return to improve reliability.

This technique was used in the first tests of the monitor system. Installation techniques used to mount strain gages on the research engine resulted in an excessive number of gage failures. When a failure occurred, it would sometimes cause an intermittant short of the common side of a gage to the engine rotor. This short induced a common mode noise signal to all of the gage amplifiers. Because the amplifier's common mode rejection decreases at higher frequencies, an unacceptable noise signal level appeared on all amplified gage signals until the short was removed. In order to minimize this problem, the gage wiring was changed to use two slip ring conductors for each strain gage (Fig. 4). This approach reduces the slip ring capacity to only 50 gages, but a short as described above will affect only the shorted gage amplifier.

Hardware

Figure 5 shows the hardware functional block diagram. Strain gage signals from the rotating shaft are sent through a 100 conductor slip ring to the signal conditioner. Each signal conditioner (Fig. 4) includes a constant current source and a two-wire circuit to each strain gage.

The use of this type of circuit is possible because flutter is a dynamic phenomenon and steady state signals are not needed. The strain gage signals are amplified by AC coupled instrumentation amplifiers to a high level and then are available to the analog signal multiplexer, FM tape recorder, and monitor oscilloscopes.

The signal conditioners incorporate a strain gage fault detector to eliminate some false alarms. This detector uses the fact that a strain gage normally will fail open or intermittently open. To detect a fault, a latching comparator monitors the voltage across the strain gage. If the gage opens or intermittently opens, the constant current source, in attempting to maintain constant current, will supply a maximum voltage much larger than that for full-scale strain, thereby setting the comparator to the "fail" state. The microprocessor resets the comparator at the start of the peak detector aperature and then reads the comparator state at the end. The comparator state then represents whether or not the gage was good during the peak aperature time.

For calibration and test purposes, a means of inserting a signal equivalent to zero, 50 and 100 percent of full scale strain in place of the strain gage signals has been incorporated in the signal conditioner circuitry (see Fig. 4).

The 96 channel multiplexer was built using six modules (16 channels each) whose outputs go to an eight-channel module. The multiplexer is controlled by the microprocessor. The output of the multiplexer is amplified to match the full-scale requirement of the peak detector.

The peak detector is used to acquire the peak value of a strain gage signal during the 10 millisecond aperature time for that gage. The commercial module used for this purpose has three operating states (reset, peak detect and hold) which are controlled by the microprocessor.

The signal from the peak detector is digitized by an eight-bit analog to digital converter. The eight-bit binary data work along with the "good" or "bad" indication from the comparator is then available to the microprocessor.

To signal an out-of-limit condition, the microprocessor uses output relays (for alarm and abort) and a three-digit light emitting diode (LED) display or a scan panel type of display for strain gage identification. A standard teletype was interfaced to the microprocessor for the entry and verification of strain gage limits.

The eight-bit microprocessor used is commercially available in a modular card form. The custom configuration to perform the monitor task was assembled by connecting the appropriate card modules. The microprocessor's 20 microsecond typical instruction time and 48 data oriented instructions were well suited to meet the overall monitor requirements. Therefore, the monitor's memory requirements of 2K words of erasable reprogrammable type (PROM) and 1K words of random access type (RAM) were easily met.

Software

The microprocessor program has been organized in three basic parts: limit entry, systems test and limit monitor.

The limit entry portion allows the initial setting of all 96 strain gage limits either by teletype keyboard or paper tape reader. It provides a means of changing individual limits without complete re-entry and a means of verification of limits by the use of the teletype printer.

The system test portion contains various routines to check-out and calibrate different parts of the system. These routines are important because they make it easier to diagnose and correct hardware problems should they occur.

The limit monitoring program transforms the hardware previously described into the multichannel strain gage monitor. The flow diagram for this microprocessor program is shown in Fig. 6. As can be seen, all control, timing and limit comparison is performed by the microprocessor program.

After program initialization, the multiplexer is set to strain gage No. 1. After allowing for multiplex settling time, the peak detector is reset and then commanded to acquire the peak of the incoming signal. The microprocessor program starts a 10 millisecond timer loop. Upon completion of the delay, the peak detector is commanded to hold its peak value. The A/D converter is commanded to convert the newly acquired peak value to an eight-bit binary word. After the proper delay, the microprocessor inputs this eight-bit word and the gage failure detector condition.

If the gage is "good," this data value is now compared to the previously stored alarm limit for strain gage No. 1. If the value is below the 1. If the value is below the limit value, the program tests the current gage number, and if the number is equal to the largest gage number, the gage number is reset to one. If the number is less than the largest gage number, the gage number is incremented by one, and the multiplexer is set to the new gage and the process is repeated. However, if the peak value is equal or above the limit, the microprocessor then repeats the peak value acquisition and the A/D conversion for the same channel. If the input value exceeds the limit value three consecutive times, the microprocessor recognizes this as an out-of-limit condition.

Next, the peak value is compared to the stored abort limit for that gage and the appropriate output relay is set. The microprocessor then outputs the gage number and the type of limit condition (alarm or abort) to the LED display or scan panel. The procedure of requiring three consecutive peak samples to be above the limit was used to improve the degree of confidence in an out-of-limit condition. Improvement, of course, was at the cost of system time response.

Results of Using System

The monitor system was used for a F-100 engine fan flutter test program. The purpose of this phase of the test program was to define engine conditions where flutter occurred. However, the test was cut short because of strain gage failures. In use, the strain gage monitor successfully detected strain gage out-of-limit conditions and distinguished between alarm and abort levels. Problems encountered while using the system were:

1. Noise which was present in analog strain signals.
2. Common ground system while the 96 strain gages were being used on a 100 conductor slip ring.
3. Lack of distinction between flutter and forced vibration because only amplitude was monitored.
4. Inability to use different stress limits for the different modes of flutter on the same gage, again because only the amplitude was monitored.

The noise signals were of two types. The first was spurious interference spikes of very short duration and random in time of occurrence. The second was an intermittent low amplitude signal whose source was identified as crosstalk in the cables from a failed strain gage whose failure mode was an intermittent open circuit. To reduce the sensitivity of the monitor to the first type of noise the program was changes, as already described, to require three consecutive samples of any strain gage all of which must exceed the stored limit for that gage before the monitor would indicate an alarm or abort condition. The crosstalk noise problem was reduced by changing gage wiring and by making provisions to switch in a short circuit across a gage as soon as it was verified as defective.

The next two problems, distinguishing between flutter and forced vibration, and using limit values as a function of frequency, are basic to the lack of frequency information in the time domain monitor system.

FREQUENCY DOMAIN SYSTEM

To solve these last two problems, a second type of strain gage monitor system is being developed. This system uses the frequency as well as the amplitude information in the strain gage signals. The frequency domain system requirements as previously stated and in addition it should:

1. Compare the amplitude vs. frequency information contained in the strain gage signal to a set of amplitude vs. frequency limits for that gage.
2. Be capable of distinguishing between flutter and forced vibration by using the fact that forced vibration frequencies are always an integer multiple of engine rpm.
3. Provide a CRT display to indicate an out-of-limit condition and graphically show the user at which frequency the gage exceeded the limit profile.
4. Allow for frequency resolution of the gage signals to as fine as 20 Hz.

To meet these requirements, the system must transform the gage signals from the time domain to the frequency domain and thereby obtain amplitude vs. frequency data. A spectrum analyzer is used to perform this transformation. Conceptually, this frequency domain system differs from the time domain system only in that the peak detector and the A/D converter are replaced by a high speed spectrum analyzer. It is not that simple however, since the introduction of a spectrum analyzer produces hundreds of times more digital data in which the microprocessor must process in performing its monitoring task. This increase in information also compounds the problem of indicating the type and frequency of the out-of-limit condition.

Design Trade-Offs

The design trade-offs for this system are related to the speed and frequency resolution of the spectrum analyzer. The faster the analyzer, the more channels per second can be monitored. The greater the analyzer frequency resolution, the more data to be checked against stored limits, resulting in inincreased program execution time and storage requirements.

Assuming that the signal spectrum is not changing with time, the time length of the signal record which must be analyzed is inversely proportional to the required frequency resolution. Using the desired frequency resolution of 20 Hz the analyzer signal record length must be 1/20 Hz or 50 milliseconds. Adding to this the 50 milliseconds required for the commercially available analyzer used to perform the transformation after getting the sample, results in 100 milliseconds per strain gage or 10 gages per second. Meeting the original requirement of sampling each gage once per 1 or 2 seconds limits the number of gages to 10 or 20. Using the 20 Hz resolution and an upper frequency limit of 10 kHz, we have 10 kHz/20 Hz or 500 data words to represent the gage signal. This means that 500 limit comparisons must be made for each gage.

Hardware

The hardware functional block diagram is shown in Fig. 7. It is very similar to the time domain system except for the addition of the spectrum analyzer and the CRT display. The strain gage signals are sent through the slip rings and to the same signal conditioning circuit as described before. The conditioned signals are displayed on individual oscilloscopes and recorded on Fm tape as before. The monitor system selects the gage to be processed by the use of the same analog multiplexer.

The spectrum analyzer used is a commercially available real-time spectrum analyzer which performs analysis with 500 line resolution. This type of analyzer uses step heterodyning and filter techniques rather than the much higher cost digital fast fourier transform techniques. The analyzer is controlled by the microprocessor using the analyzer's digital interface option. In operation, the selected signal is first stored (50 milliseconds) and then processed (50 milliseconds) by the spectrum analyzer. During the 50 milliseconds that the analyzer is processing each gage signal it sends all 500 data words (once every 100 microseconds) to the microprocessor. These represent the amplitudes of the spectral lines. The result of an out-of-limit condition is the closure of an output relay contact as well as a special display on the CRT screen. It is possible (though we have not implemented this) to generate a hard copy of the display on user demand by the use of a standard peripheral device to the CRT display.

Because of the previously stated data requirements (quantity and rate) of the spectrum analyzer and the CRT display demands, it is necessary to use a more powerful microprocessor than the eight-bit machine used in the time domain system. The 16-bit microprocessor that will be used is built around a set of four N-channel metal oxide semiconductor chips. It is, as before, commercially available in a modular card form. The custom configuration to perform the monitor task was assembled by using the appropriate card modules. With a typical 3-microsecond instruction execution time and over possible instructions, the microprocessor meets the monitor requirements.

Software

The microprocessor program has, as before, been organized in three basic parts; limit entry, system test and limit monitor. The first two parts serve the same function as they did in the time domain system except they must relate to different hardware and use a limit profile representing 500 limits for each strain gage. The flow diagram for the limit monitor program is shown in Fig. 8. The program forms CRT display, controls gage selection, performs limit checking and alarming and performs system timing. Using the fact that the spectrum analyzer needs 50 milliseconds to sample data and then another 50 milliseconds to process and output the spectra, it is convenient to separate the program into two parts each utilizing 50 milliseconds.

During the first 50 millisecond part, the microprocessor commands the analog multiplexer to the proper gage. The spectrum analyzer is then commanded to acquire its 50 milliseconds of data. While this is happening, the microprocessor formats and sends a display to the CRT. This spectrum display will normally be that of a user requested gage (Fig. 9). However, in the case of an out-of-limit condition, the requested gage will be replaced by the gage whose signal exceeds the limit profile by the maximum amount. The out-of-limit display also shows the appropriate limit profile, as well as the gage spectra, (Fig. 10).

The second 50 millisecond part is used to read the spectral data, refresh the CRT display, and compare the new gage spectrum to its unique limit profile. The spectral data is received from the spectrum analyzer, one word every 100 microseconds, and can be stored by the microprocessor in less than 20 microseconds. Then the microprocessor can use the time between data words to refresh the CRT.

After the 500 spectra lines are received and each line is compared to its unique limit, the microprocessor switches the multiplexer to the next gage and repeats the monitoring procedure. However, if during the comparison the microprocessor finds that any spectra line exceeds its appropriate limit, the microprocessor will set the alarm relay and change the CRT display from the user requested gage to the out-of-limit gage.

Results of Using the System

At the time of writing this report, the system has been implemented as a prototype system. This prototype system is identical to the anticipated final monitor system except for the microprocessor. The prototype system uses a minicomputer to perform all of the functions required of the microprocessor. The prototype system is being used to develop the software for the monitor. When the microprocessor is received and installed, this developed software will be used.

CONCLUDING REMARKS

When performing flutter research test programs, a multichannel monitor system is not only desirable but is necessary. The time domain monitor meets the basic requirements of a flutter monitor because it does alarm test personnel of a high stress condition in the test article, but it does not necessarily indicate that this condition is caused by flutter. The frequency domain monitor system has the capability of evaluating the amplitude and the frequency content of a strain gage signal. Using this capability and the proper judgment criteria in the microprocessor program, the monitor system can distinguish flutter from other engine phenomena.

The most outstanding feature gained by using a microprocessor in the monitor is its adaptability to the use of new criteria for flutter detection by a change in the microprocessor program. Because of this feature, the microprocessor-based multichannel flutter monitor could easily be used for critical monitoring tasks other than flutter.

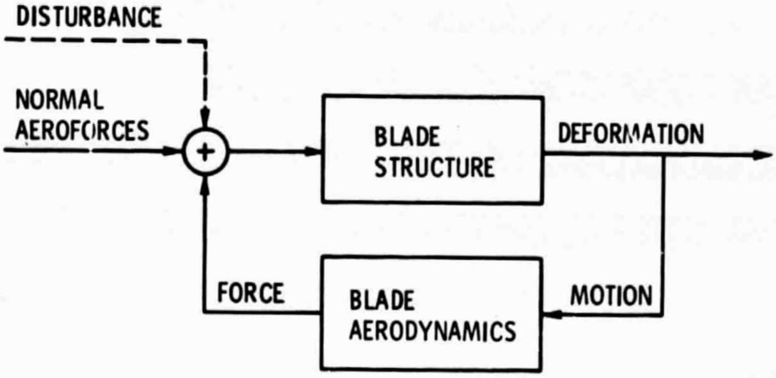

Figure 1. - Blade flutter system.

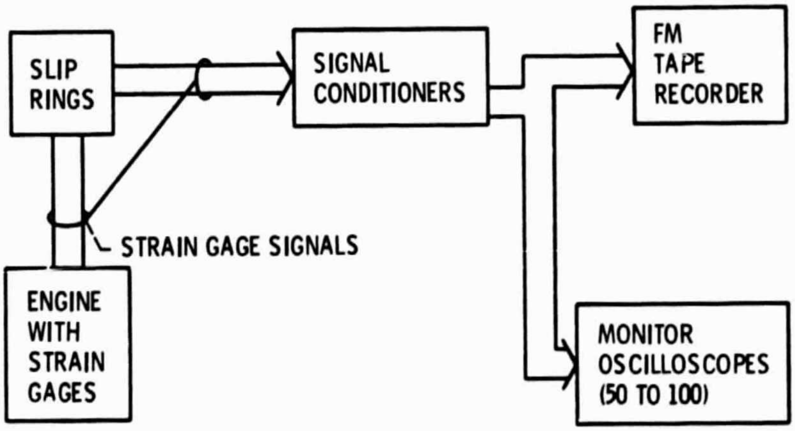

Figure 2. - Conventional flutter monitoring system.

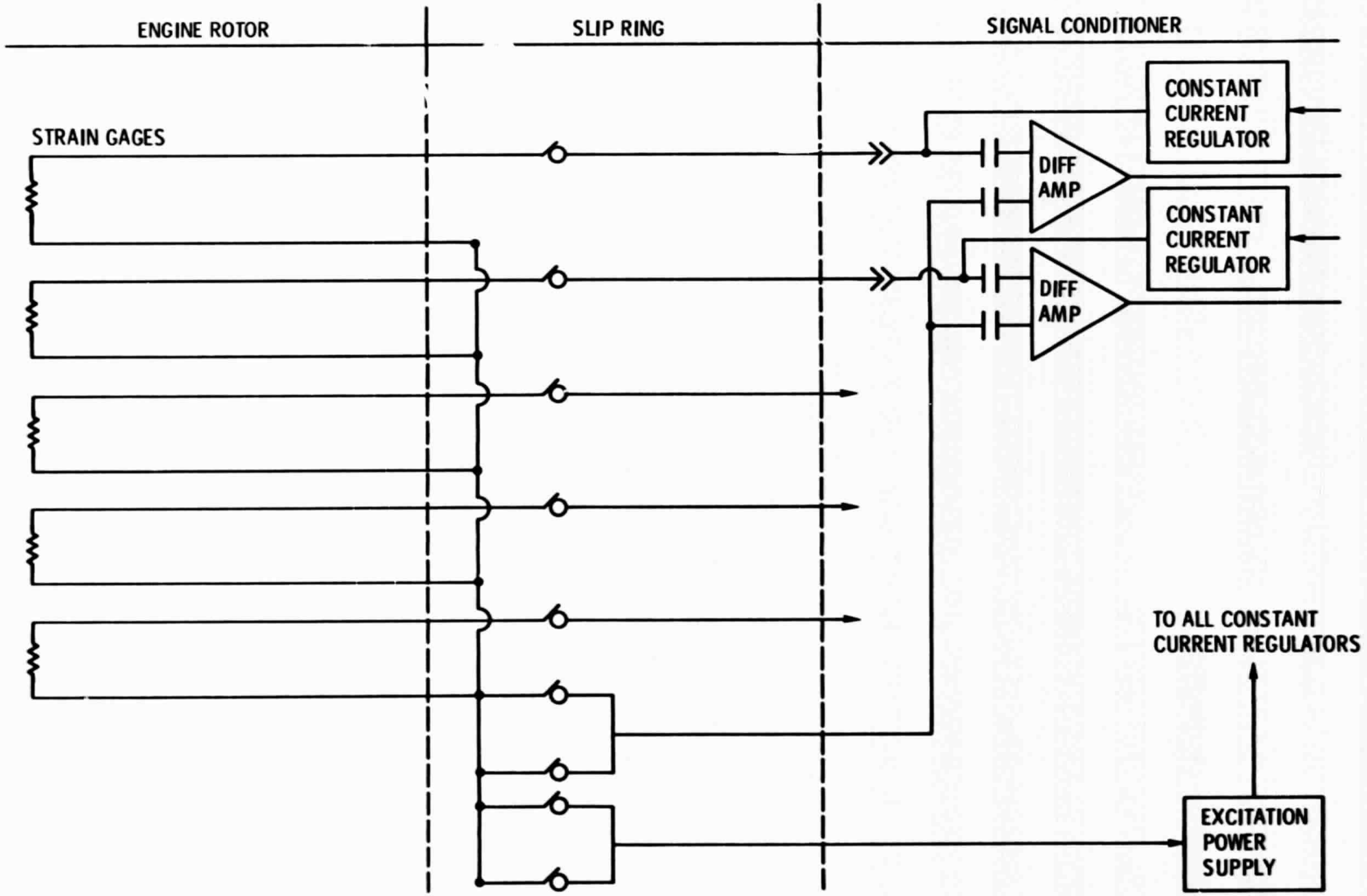

Figure 3. - Strain gage wiring for 96 gages using 100 conductor slip ring.

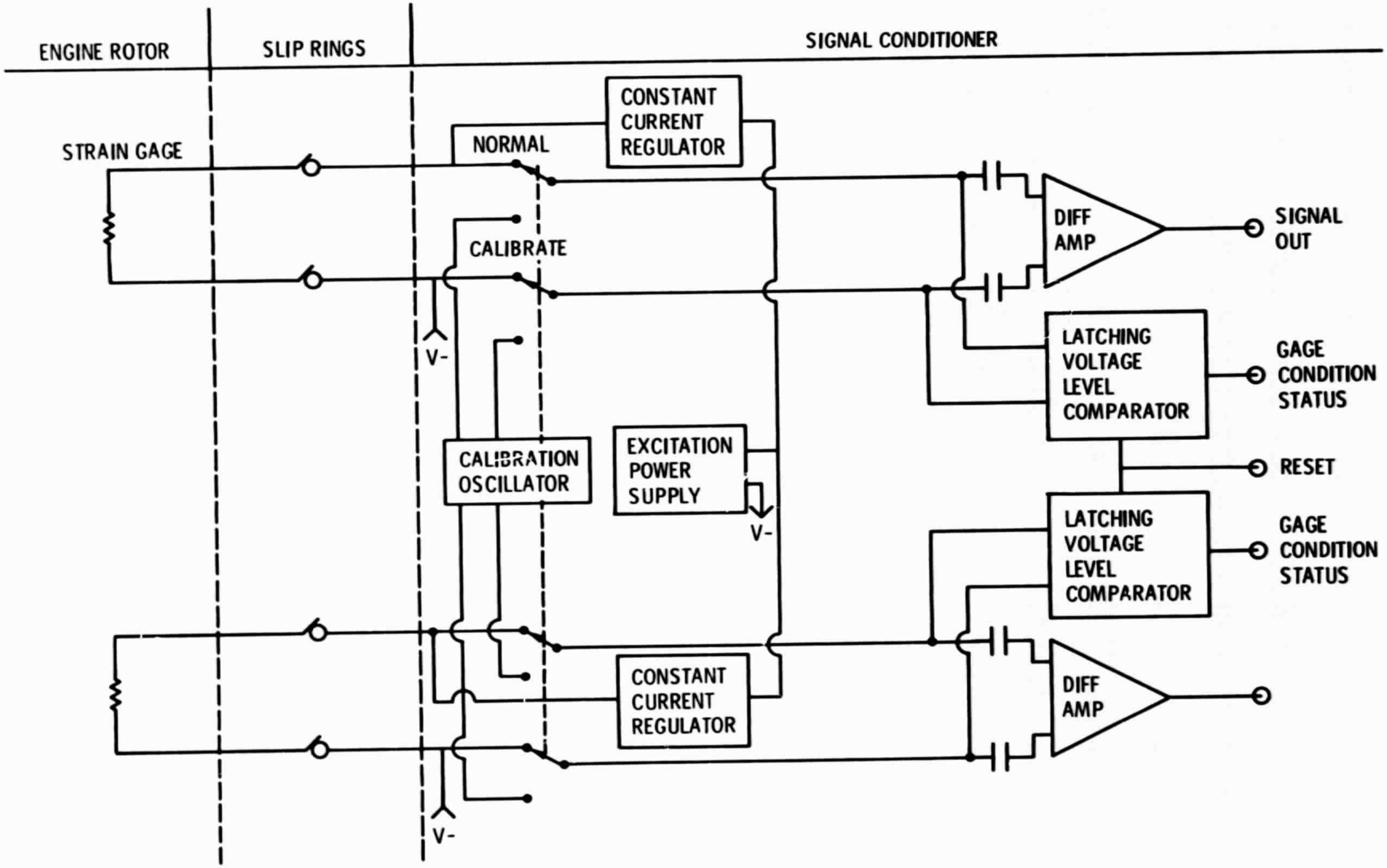

Figure 4. - Strain gage wiring for 50 gages using 100 conductor slip ring.

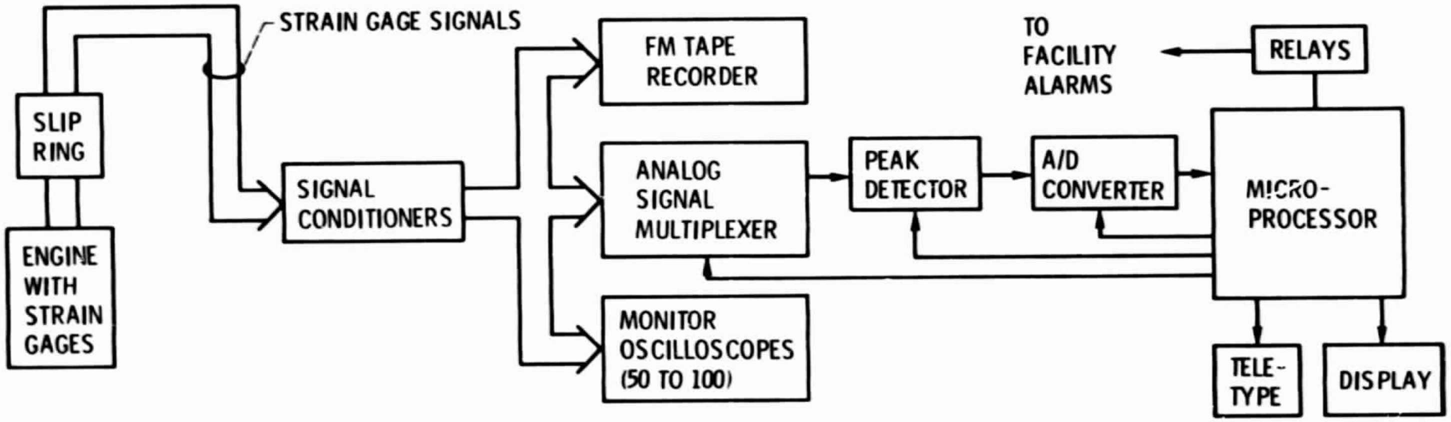

Figure 5. - Time domain system hardware functional block diagram.

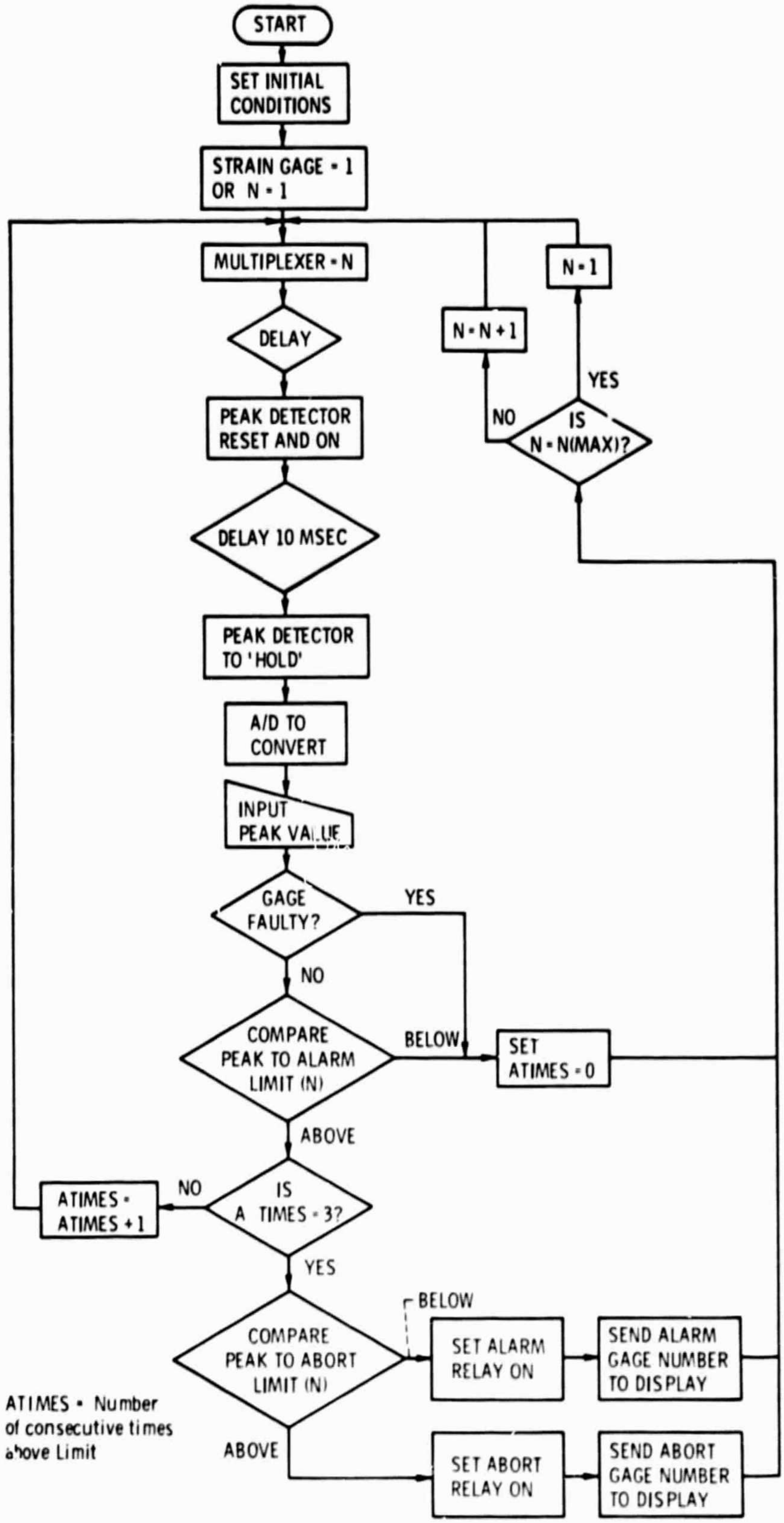

Figure 6. - Time domain system flow diagram.

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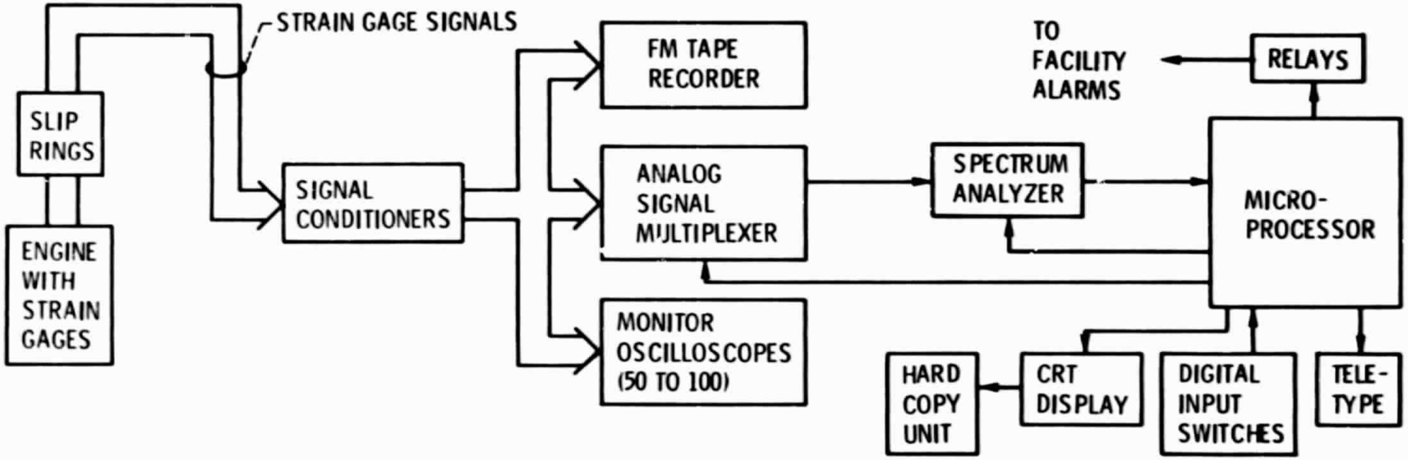

Figure 7. - Frequency domain system hardware functional block diagram.

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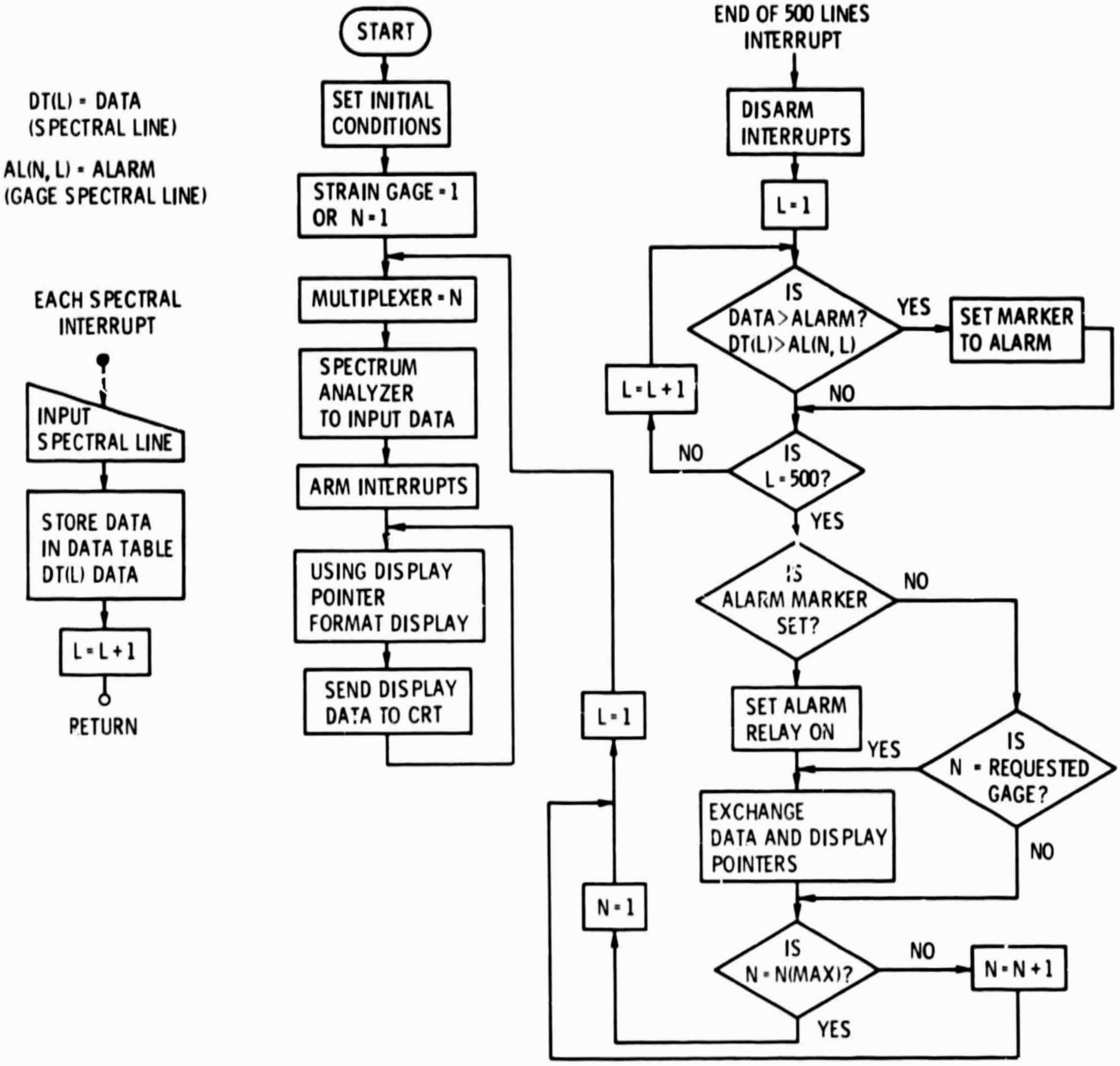

Figure 8. - Frequency domain system flow diagram.

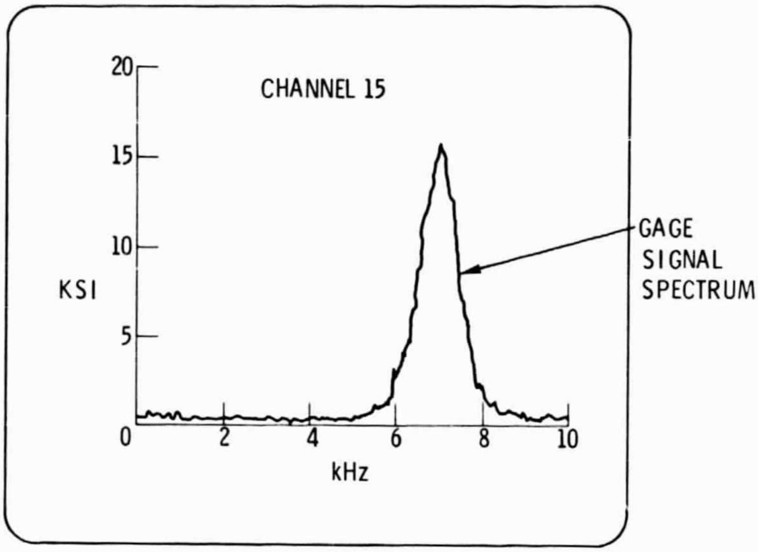

Figure 9. - Display of user requested gage.

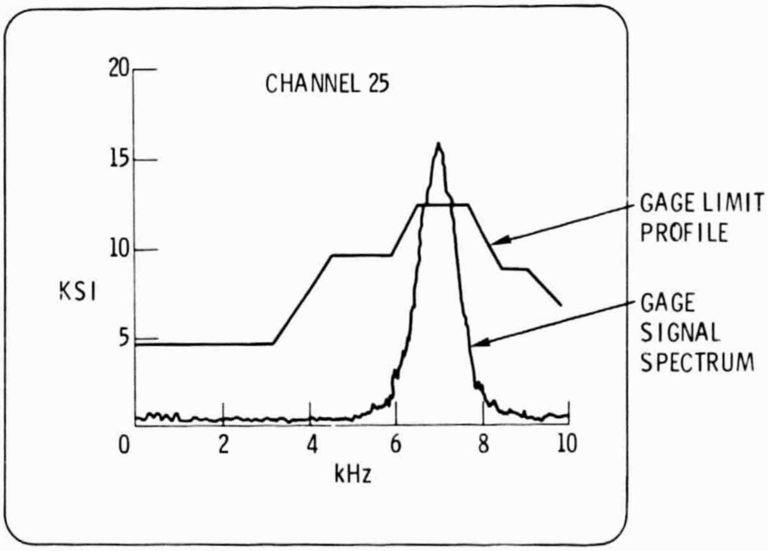

Figure 10. - Display of gage in alarm condition.