NASA TECHNICAL NOTE

NASA TN D-5944

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NASA TN D-5944

AN ELECTRONIC STRAIN-LEVEL COUNTER FOR AIRCRAFT STRUCTURAL MEMBERS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1970

1. Report No. NASA TN D-5944	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AN ELECTRONIC STRAIN-LEVEL COUNTER FOR AIRCRAFT STRUCTURAL MEMBERS		5. Report Date September 1970
		6. Performing Organization Code
7. Author(s) Felix L. Pitts and J. Larry Spencer		8. Performing Organization Report No. L-7190
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 126-14-15-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s)) Electronic strain-level counter Aircraft structural-fatigue instrumentation Counting strain gage Strain-gage instrumentation Integrated circuits	18. Distribution Statement Unclassified – Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	17	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

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SUMMARY

The description and test results of an electronic strain-level counter designed for obtaining structural-strain data on in-flight aircraft are presented. The device counts the number of times the strain at a point in a structural member exceeds each of four preset levels. A dead band is provided at each level to prohibit the counting of small strain variations around a given preset level. A resistance strain gage is used as the sensor, microelectronic and discrete solid-state circuits are used for signal processing, and electromechanical counters are used for data storage.

INTRODUCTION

Structural-fatigue assessment of in-service aircraft is based primarily on visual and X-ray inspection procedures. An electronic device which counts the number of times the strain at a point in a structural member exceeds each of four preset levels has been developed as a candidate system to augment these established procedures. The complexity of structural-fatigue assessment of aircraft does not allow structural-lifetime prediction to be based entirely on data generated by strain-level counters. However, use of the strain counters in a fleet of aircraft could yield a statistical-data body on the number and severity of in-service structural strains. Based on this information, a graduated scale of aircraft-use severity could be generated and used to aid in scheduling inspection and maintenance. In addition, correlation of the data with observed fatigue failures might aid in general fatigue assessment of aircraft of the same type.

A strain-level counter for use on in-service aircraft, in addition to being accurate and reliable, should satisfy the following requirements: The installation must not introduce structural defects, the installation should be relatively easy with minimum interface requirements, the device should require little maintenance, and the data readout should be simple. Use of the electronic strain-level counter, which is representative of systems that interface with the aircraft power supply, is one approach to satisfying these requirements. Flight testing of the electronic strain-level counter is planned to evaluate its performance and utility for comparison with other devices such as the mechanical scratch gage evaluated in reference 1.

SYMBOLS

A	amplifier gain
E	bridge excitation
e_o	amplifier output
e_o'	bridge output
F	bridge gage factor
R,R_1,R_2	resistances of resistors R, R_1, and R_2, respectively
R_n	nominal bridge resistance
V_h	hysteresis voltage
V_{lt}	lower threshold voltage
$V_{o,f}$	output voltage of flip-flop
$\left(V_{o,f}\right)_{max}$	maximum output of flip-flop
$\left(V_{o,f}\right)_{min}$	minimum output of flip-flop
V_r	dc-reference voltage
V_t	voltage on noninverting input (+) of comparator
V_{ut}	upper threshold voltage
ϵ	strain applied to gage

SYSTEM DESCRIPTION

The strain-level counter counts the number of times the strain at a point in a structural member exceeds each of four preset levels. By using hysteresis, a dead band is provided at each level so that after the strain exceeds a given level and a count is registered, the strain must decrease below the dead band and then increase again before another count is registered. The adjustable dead band prohibits the counting of small strain variations due to flexural oscillations around a given level. This strain-level counter and other devices such as the fatigue meter which disregard small load variations yield similar results when applied to several load-time histories. (See ref. 2.)

In the present system, a separate counter counts the exceedances of each of four strain levels: three positive levels and one negative level. The nominal strain levels are 3.0×10^{-3}, 1.5×10^{-3}, 0.5×10^{-3}, and -0.5×10^{-3}. The system uses a metallic resistance strain gage as the sensor, microelectronic and discrete solid-state circuits for signal processing, and electromechanical counters for data storage. Each counter can accumulate up to 9999 counts. The system contains voltage-regulator circuitry and interfaces with 28-volt dc power. Figure 1 is a photograph of the packaged system. The size is 8.2 by 4.8 by 1.7 inches (20.8 by 12.2 by 4.3 cm), exclusive of the counters, which are contained in a removable package measuring 1.2 by 1.4 by 6.4 inches (3.0 by 3.6 by 16.3 cm). The weight of the total system is 2.5 pounds (1.14 kg).

A simplified block diagram of the system is shown in figure 2. The bridge output is a low-level differential analog voltage proportional to the applied strain. This low-level signal is amplified and used as an input to a level detector with hysteresis, which has a transfer function as shown in figure 3. As the input increases through a preset upper threshold V_{ut}, the state of the output changes from high to low. As shown by figure 3, the state of the output cannot change again until the input decreases below a preset lower threshold V_{lt}. The hysteresis voltage V_h for each level represents a strain of 0.3×10^{-3}. When the input increases through V_{ut}, a pulse is generated to drive an electromechanical counter.

In order to circumvent the drift problems of dc-coupled amplifiers, ac bridge excitation obtained from an astable multivibrator was employed in the system as shown in figure 4. The output from the bridge is a pulse train with an amplitude proportional to the strain input. This signal is amplified by an ac-coupled amplifier. The output of the amplifier is coupled to the level detectors, which are enabled during each data pulse by the signal from the strobe-pulse generator. The astable multivibrator also provides the input to the strobe-pulse generator. When the amplitude of the data pulse exceeds a preset level, a signal generated by the level detector causes a count to be registered in an electromechanical counter. A detailed explanation of the signal processing is given in the appendix. The following briefly describes the electronic subsystems which are shown in the schematic diagram of figure 5.

ELECTRONIC SUBSYSTEMS

Power Supply

The strain-level counter operates from a nominal 28-volt dc supply. The system requires 300 mA while on standby and an additional 50 mA during each count operation. The supply voltage for the system is filtered and then regulated to 19.8 volts by an integrated-circuit voltage regulator. From the regulated 19.8 volts, the required voltage levels for the system components are obtained by voltage dividers which use resistors and zener diodes. In order to allow the electronic components to reach steady-state operating conditions after a power dropout, a circuit is provided which prohibits counting until 50 msec after occurrence of a dropout transient severe enough to disturb the regulator output.

Astable Multivibrator

The excitation for the strain gage is obtained from an astable multivibrator with a frequency of approximately 90 hertz and a pulse duration of approximately 0.5 msec. The pulse duration of the multivibrator is long enough to allow all system transients to decay before the level detector is enabled.

Amplifier

The amplifier consists of an integrated-circuit operational amplifier with a closed-loop gain which is determined by the feedback resistor and the output impedance of the strain-gage bridge. The amplifier output is capacitively coupled to the comparators so that dc drift does not affect the system performance as long as it is not severe enough to cause saturation. Potentiometer controls are provided for adjustment of the bridge and amplifier balance.

Strobe-Pulse Generator

The strobe-pulse generator is an integrated-circuit one-shot multivibrator that is triggered on by the astable multivibrator at the beginning of the excitation pulse and switches off to enable the level detector. The enabling time is determined by the value of the external capacitor of the one-shot multivibrator.

Level Detectors With Hysteresis

A level detector is provided for each of the four preset strain levels. Each level detector consists of an integrated-circuit comparator, an adjustable dc reference source, and a flip-flop with an output which is resistively fed back to one of the comparator inputs to obtain hysteresis. Potentiometer controls are provided for adjustment of the upper threshold and the hysteresis.

Drive Circuit and Counter

The function of the drive circuit and counter is to register 1 count for each negative transition of the level detector with hysteresis. The negative transition triggers a one-shot multivibrator to produce a voltage pulse of 20-msec duration to drive the electromechanical counter.

TEST RESULTS

The electronic system, exclusive of the strain gage, was tested for accuracy as a function of ambient temperature ranging from -65° to 200° F (-53.8° to 93.3° C) and power-supply voltage ranging from 24 to 32 volts. The input strain to the system was simulated by use of shunt resistance across one leg of a resistive bridge. Table I shows the simulated strain levels required to trip the high-, medium-, low-, and negative-level counters (nominal strains of 3.0×10^{-3}, 1.5×10^{-3}, 0.5×10^{-3}, and -0.5×10^{-3}, respectively) at various temperatures and power-supply voltages. The maximum variations of strain over the ranges of temperature and power-supply voltage are 6.1×10^{-5}, 3.1×10^{-5}, 2.7×10^{-5}, and 3.3×10^{-5} for the high-, medium-, low-, and negative-level counters, respectively. In figure 6, the percent error of the nominal strain required to trip each counter is plotted as a function of ambient temperature with supply voltage as a parameter. These data are normalized with respect to the nominal trip level for a given channel, which is defined as the strain required to trip a given counter at a temperature of 70° F (21.1° C) and a power-supply voltage of 28 volts.

The percent error of the strain required to trip each counter is defined as

$$\text{Percent error} = \frac{S - S_n}{S_n} 100$$

where S is the strain level required to trip the counter at test temperature and supply voltage and S_n is the strain level required to trip the counter at nominal room temperature, 70° F (21.1° C), and nominal supply voltage, 28 volts dc. For example, the strain level required to trip the medium-level counter at 70° F (21.1° C) and 28 volts dc is 1.492×10^{-3}, and the strain level required to trip this counter at 200° F (93.3° C) and 32 volts dc is 1.511×10^{-3}. The resulting percent error is

$$\text{Percent error} = \frac{(1.511 - 1.492) \times 10^{-3}}{1.492 \times 10^{-3}} 100$$

$$\text{Percent error} = 1.27$$

It should be noted that these data represent the percent error for a particular level counter and not (except for the high-level counter) the percent error of the full-scale strain of 3.0×10^{-3}. Expressed as a percent of full scale, the maximum error is 2.04 percent for the high-level counter, 1.04 percent for the medium-level counter, 0.905 percent for the low-level counter, and 1.10 percent for the negative-level counter over the ranges of temperature and power-supply voltage.

The system was tested for spurious counts due to power-supply voltage transients. Positive and negative transients, each having approximately a 70-volt peak and a 250-μsec duration, were superimposed on the nominal 28-volt supply. The system was subjected to 100 positive transients and 100 negative transients and no spurious counts on any of the four counters were observed.

Shock, vibration, and crash-safety qualification tests were performed on the prototype system in accordance with Military Standard 810B (ref. 3) for propeller-driven and jet aircraft. There were no changes in system performance as a result of these tests.

CONCLUDING REMARKS

A flight-worthy, electronic strain-level counter has been developed and qualified for installation on aircraft to obtain in-flight structural-strain data. A maximum error of approximately 2 percent of full scale was obtained for ambient temperature ranging from -65° to 200° F (-53.8° to 93.3° C) and power-supply voltage ranging from 24 to 32 volts dc. Positive and negative power-supply transients, each having approximately a 70-volt peak and a 250-μsec duration applied to the power leads did not cause spurious response. Shock, vibration, and crash-safety tests indicated that accurate and reliable operation can be realized with this instrument system.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., July 13, 1970.

APPENDIX

SIGNAL PROCESSING

As many as four active strain-gage elements can be employed with the strain-level counter. For analysis purposes, a single active-element bridge was connected to the operational amplifier as shown in figure 7. The nominal bridge resistances are R_n, the change in resistance due to applied strain is ΔR_n, the bridge excitation is E, the bridge output is e_o', the feedback resistance is R, and the amplifier output is e_o.

The bridge output is

$$e_o' = E\left(\frac{R_n}{2R_n} - \frac{R_n + \Delta R_n}{2R_n + \Delta R_n}\right) \tag{A1}$$

The change in gage resistance is much smaller than the nominal gage resistance, that is, $\Delta R_n << R_n$; therefore, equation (A1) can be reduced to

$$e_o' = \frac{-E\ \Delta R_n}{4R_n} \tag{A2}$$

For the connection shown in figure 7 and for $\Delta R_n << R_n$, the amplifier gain A is

$$A = \frac{-2R}{R_n} \tag{A3}$$

The output voltage of the operational amplifier becomes

$$e_o = Ae_o' = \frac{-2R}{R_n}\frac{-E\ \Delta R_n}{4R_n} \tag{A4}$$

which is reduced to

$$e_o = \frac{RE\ \Delta R_n}{2R_n^2} \tag{A5}$$

The expression which relates the change in resistance to the strain applied to the strain gage is

$$\epsilon = \frac{1}{F}\frac{\Delta R_n}{R_n} \tag{A6}$$

where F is the gage factor of the bridge (typically $F \approx 2.1$) and ϵ is the strain applied to the gage. By combining equations (A5) and (A6), e_o becomes

$$e_o = \frac{RE\epsilon F}{2R_n} \tag{A7}$$

The value of feedback resistance needed to make e_o equal to nominally 4 volts full scale when the strain on the gage is 3.0×10^{-3} is calculated by use of

$$R = \frac{2R_n e_o}{E \epsilon F} \tag{A8}$$

which is a rearrangement of equation (A7). In the system under consideration

$R_n = 349.6$ ohms

$F = 2.1$

$E = 4.43$ volts

and the feedback resistance was calculated to be approximately 100 000 ohms.

The output of the amplifier is capacitively coupled to the level detector with hysteresis. The level detector consists of a voltage comparator, a D-type flip-flop, a resistive voltage divider, and a dc-voltage reference connected as shown in figure 7.

The function of the level-detector circuitry is to compare the amplitude of the pulse from the amplifier with a preset level at each positive transition of the strobe input. Positive feedback from the output of the flip-flop to the input of the comparator through R_2 enables the circuit to have hysteresis. The voltage on the noninverting input (+) of the comparator is denoted by V_t and is described by

$$V_t = V_r + \frac{R_1\left(V_{o,f} - V_r\right)}{R_1 + R_2} \tag{A9}$$

where V_r is the voltage of the dc reference and $V_{o,f}$ is the output voltage of the flip-flop. The comparator is connected to the D-type flip-flop so that when the strobe input changes from a low binary state to a high binary state, the output of the flip-flop assumes the same binary state as the comparator output. The flip-flop is enabled after all transients on the signal pulse have decayed. Figure 8 shows the timing relationship between the bridge excitation, amplifier output, and strobe pulse.

With zero strain on the resistive strain gage, the amplifier-output signal level during enabling is zero and the outputs of both the comparator and the flip-flop are high. When the output of the flip-flop is high, the voltage on the noninverting input (+) of the comparator V_t is defined to be the upper threshold voltage V_{ut} (see fig. 3) and is described by

$$V_{ut} = V_r + \frac{R_1\left[\left(V_{o,f}\right)_{max} - V_r\right]}{R_1 + R_2} \tag{A10}$$

Once the input signal exceeds V_{ut}, the output of the comparator becomes low during the signal pulse and the output of the flip-flop changes from a high to a low state at the positive transition of the strobe input. This negative transition of the flip-flop activates the drive circuit and counter so that the exceedance of the preset level of strain is counted. When the output of the flip-flop changes from a high $\left(V_{o,f}\right)_{max}$ to a low state $\left(V_{o,f}\right)_{min}$, the voltage at the comparator noninverting terminal decreases because of the positive feedback through R_2. This lower V_t is defined to be the lower threshold V_{lt} and is described by

$$V_{lt} = V_r + \frac{R_1\left[\left(V_{o,f}\right)_{min} - V_r\right]}{R_1 + R_2} \tag{A11}$$

The output of the flip-flop becomes high again only when the signal pulse amplitude decreases to a value below V_{lt} and a positive transition of the strobe pulse occurs. The hysteresis voltage V_h of the system is given by

$$V_h = V_{ut} - V_{lt} = \frac{R_1\left[\left(V_{o,f}\right)_{max} - \left(V_{o,f}\right)_{min}\right]}{R_1 + R_2} \tag{A12}$$

Calibration of the system is accomplished by use of a shunt resistance across one leg of the bridge to simulate a desired strain level. The upper threshold for each channel of the level detector is set by adjusting V_r and the hysteresis is set by adjusting R_1.

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1. Haglage, T. L.; and Wood, H. A.: Scratch Strain Gage Evaluation. AFFDL-TR-69-25, U.S. Air Force, July 1969.
2. Schijve, J.: The Analysis of Random Load-Time Histories With Relation to Fatigue Tests and Life Calculations. Fatigue of Aircraft Structures, W. Barrois and E. L. Ripley, eds., Macmillan Co., 1963, pp. 115-149.
3. Anon.: Environmental Test Methods. MIL-STD-810B, U.S. Dep. Def., June 15, 1967. (Supersedes MIL-STD-810A(USAF), June 23, 1964.)

TABLE I.- STRAIN LEVELS REQUIRED TO TRIP COUNTERS AT VARIOUS TEMPERATURES AND SUPPLY VOLTAGES

Temperature		Strain level required for a supply voltage of –		
°F	°C	24 V	28 V	32 V
High-level counter (nominal strain of 3.0×10^{-3})				
-65	-53.8	3.008×10^{-3}	3.011×10^{-3}	3.008×10^{-3}
0	-17.8	2.972	2.969	2.969
70	21.1	2.986	2.983	2.982
135	57.2	3.017	3.019	3.019
200	93.3	3.030	3.028	3.027
Medium-level counter (nominal strain of 1.5×10^{-3})				
-65	-53.8	1.516×10^{-3}	1.517×10^{-3}	1.516×10^{-3}
0	-17.8	1.487	1.486	1.486
70	21.1	1.495	1.492	1.493
135	57.2	1.511	1.515	1.515
200	93.3	1.513	1.512	1.511
Low-level counter (nominal strain of 0.5×10^{-3})				
-65	-53.8	0.515×10^{-3}	0.517×10^{-3}	0.516×10^{-3}
0	-17.8	.491	.490	.490
70	21.1	.496	.493	.493
135	57.2	.505	.510	.507
200	93.3	.505	.498	.502
Negative-level counter (nominal strain of -0.5×10^{-3})				
-65	-53.8	-0.483×10^{-3}	-0.483×10^{-3}	-0.482×10^{-3}
0	-17.8	-.508	-.510	-.508
70	21.1	-.502	-.505	-.504
135	57.2	-.508	-.503	-.506
200	93.3	-.513	-.515	-.515

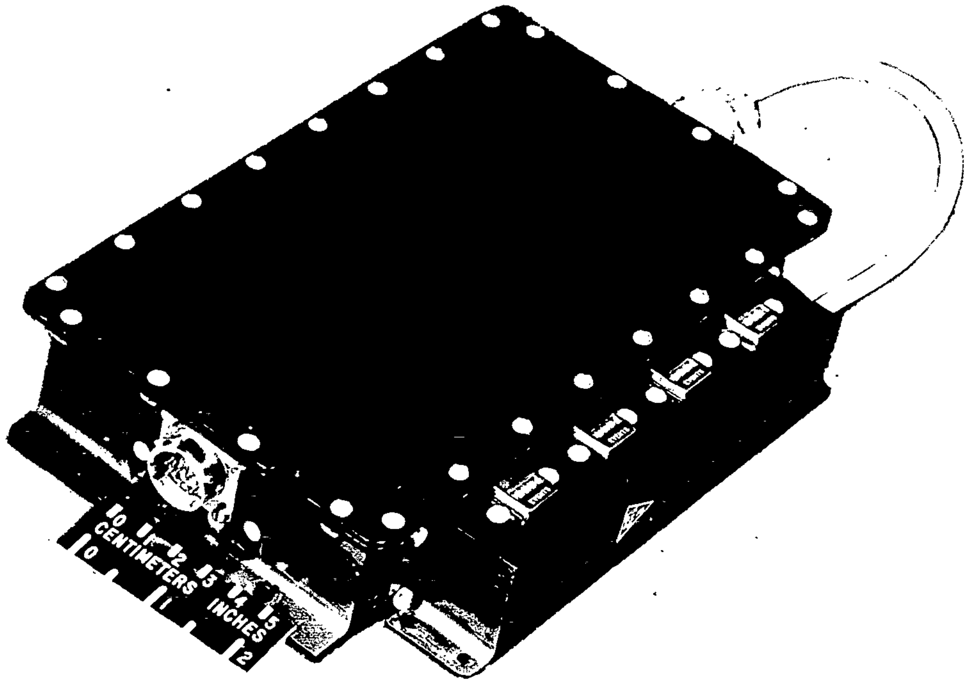

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Figure 1.- Packaged system.

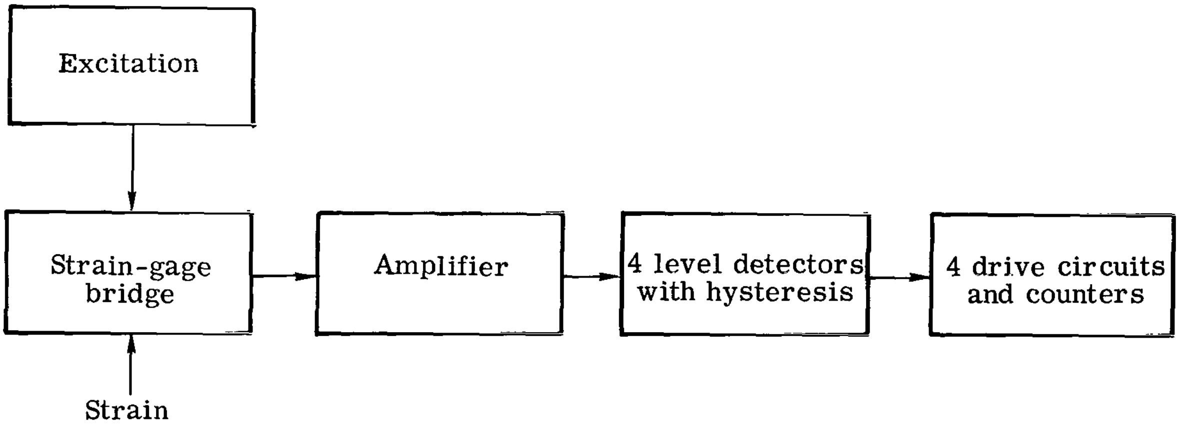


Figure 2.- Simplified block diagram of system.

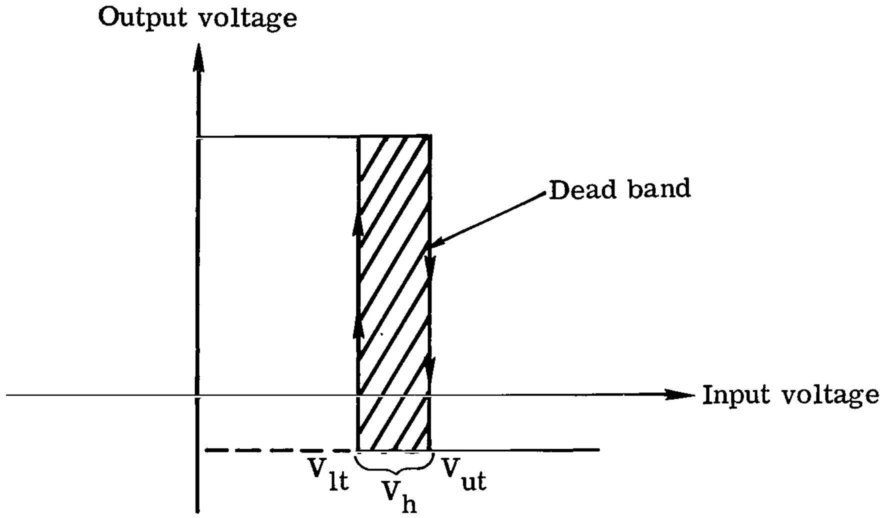


Figure 3.- Transfer function of level detector with hysteresis.

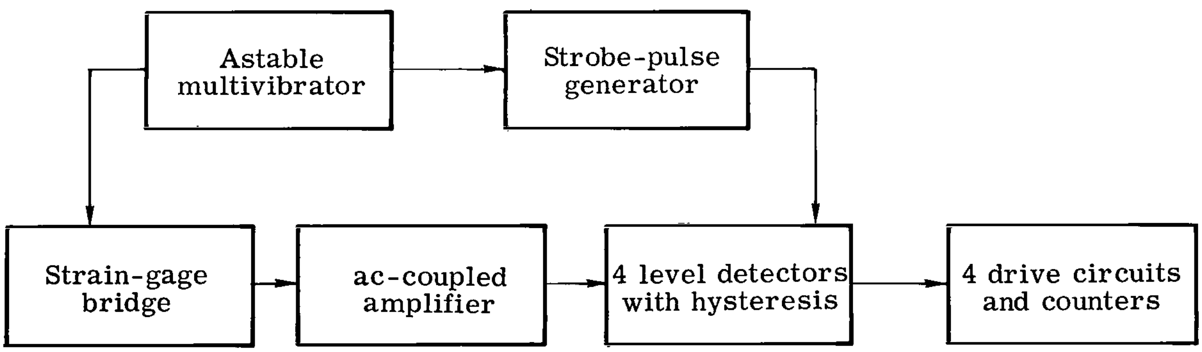


Figure 4.- Block diagram of system.

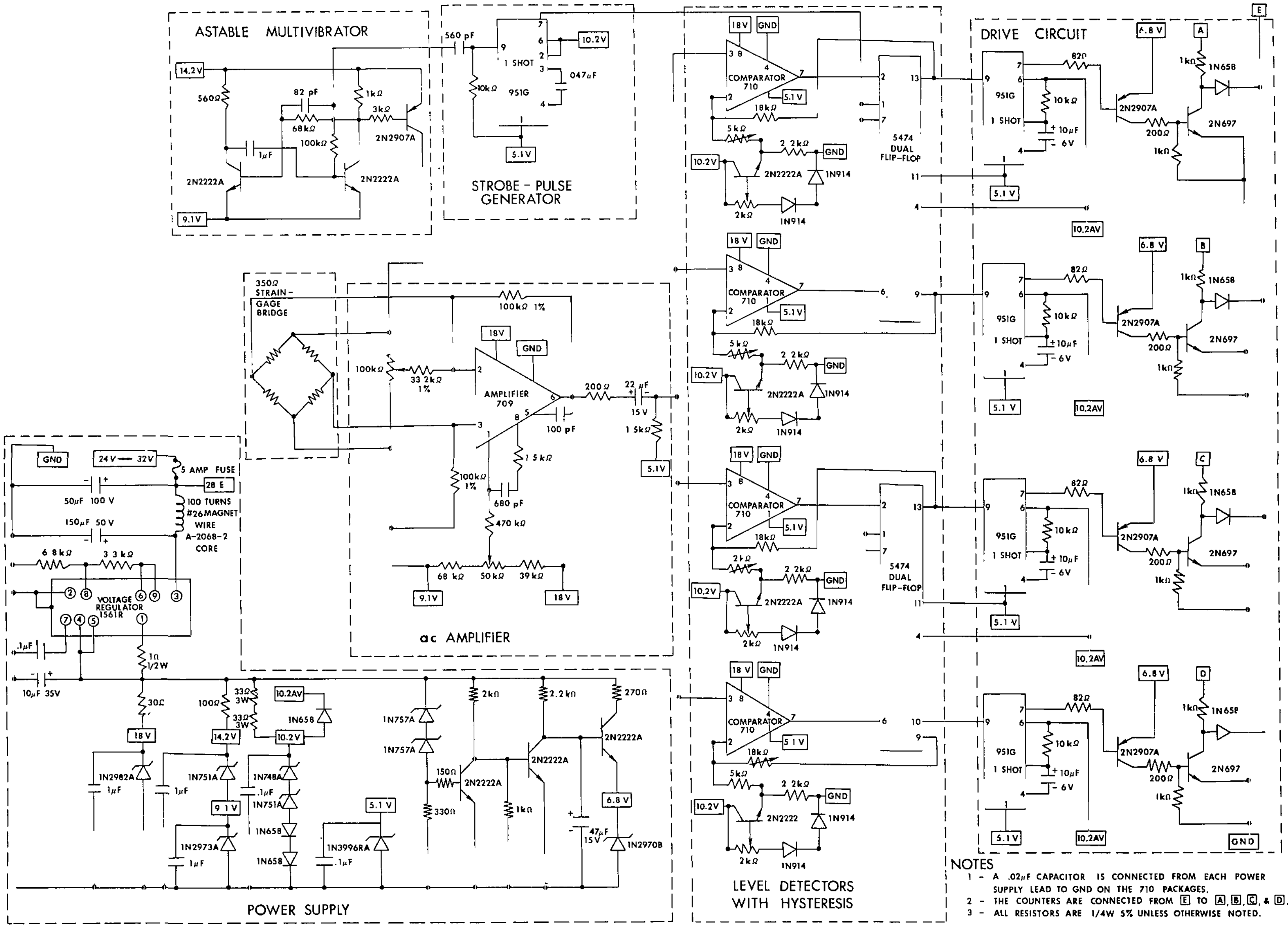
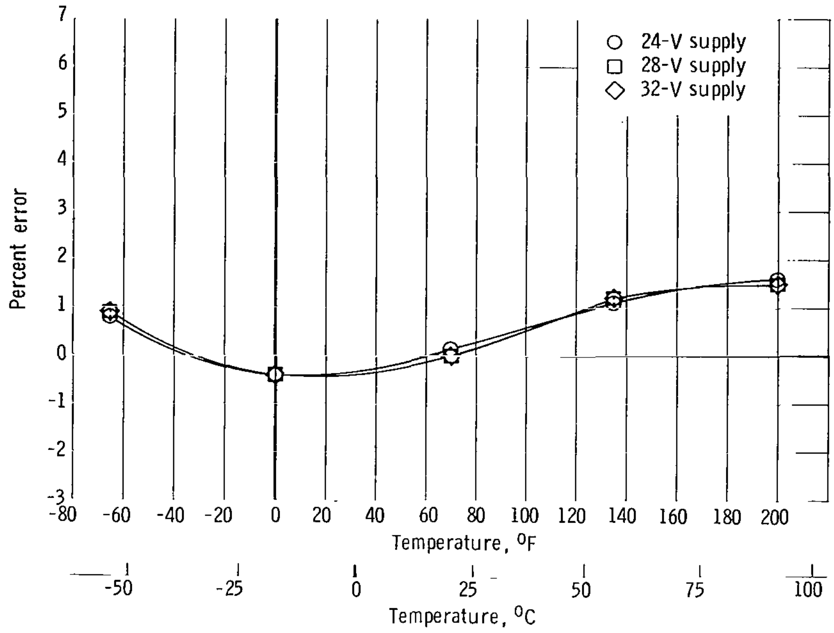
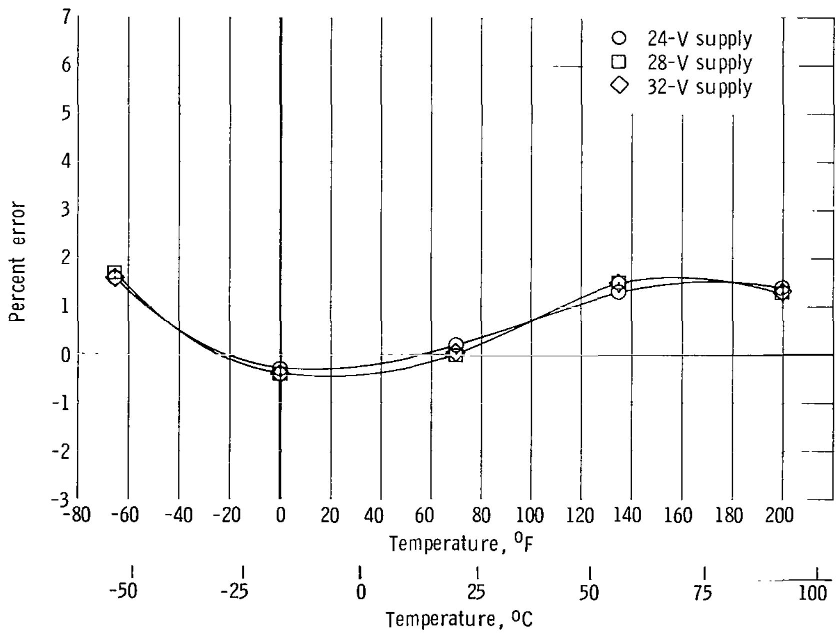


Figure 5.- Schematic diagram of system.

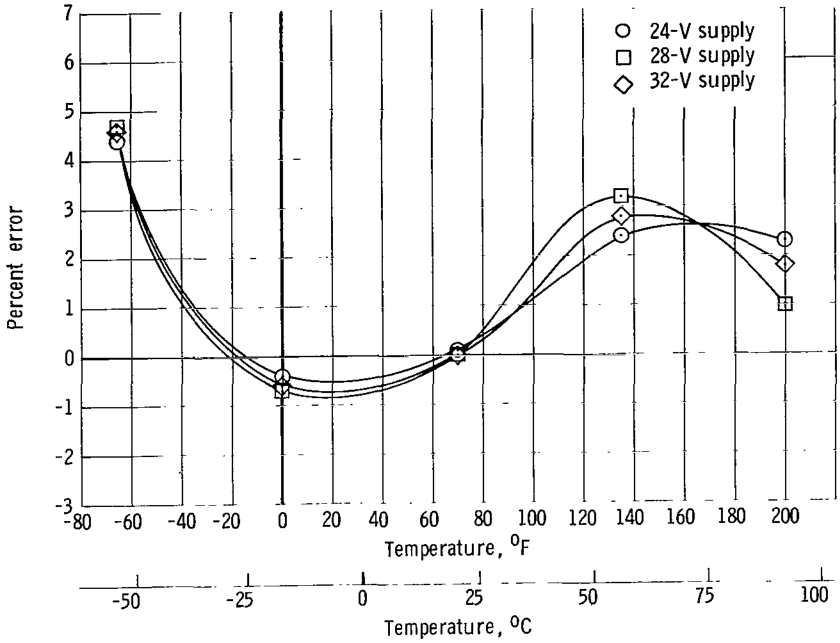


(a) High-level counter (nominal strain of 3.0×10^{-3}).

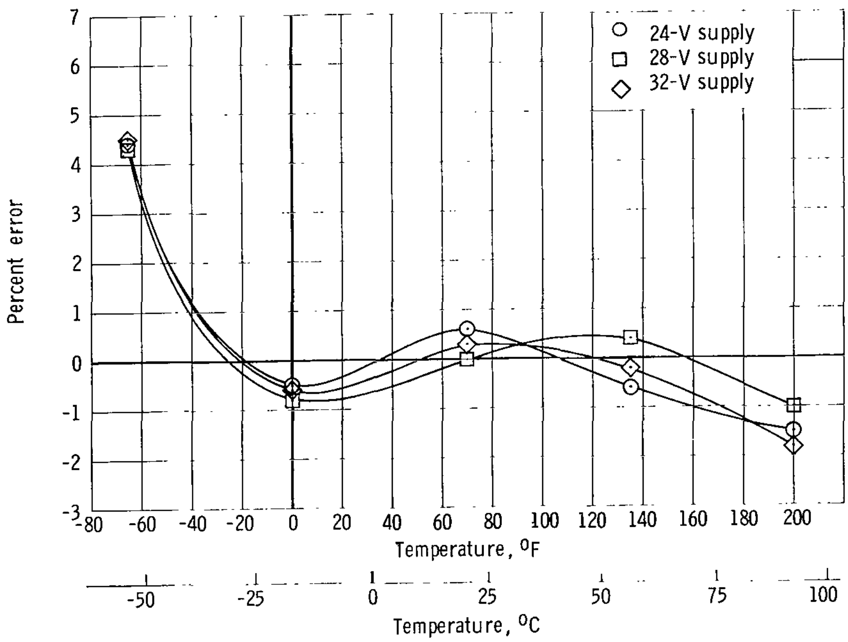


(b) Medium-level counter (nominal strain of 1.5×10^{-3}).

Figure 6.- Percent error of nominal strain required to trip high-, medium-, low-, and negative-level counters.



(c) Low-level counter (nominal strain of 0.5×10^{-3}).



(d) Negative-level counter (nominal strain of -0.5×10^{-3}).

Figure 6.- Concluded.

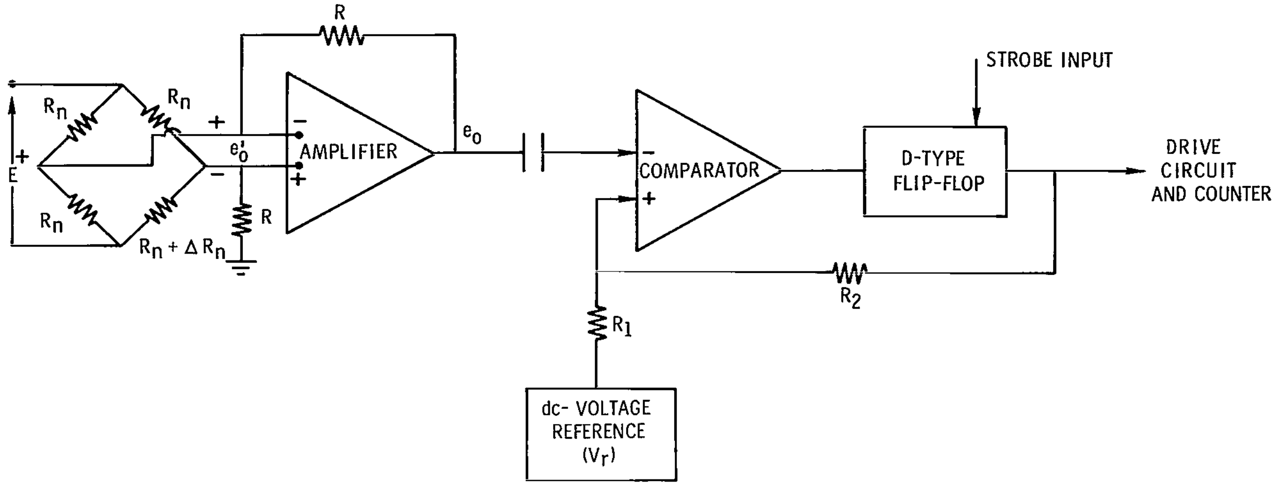


Figure 7.- Signal processing schematic.

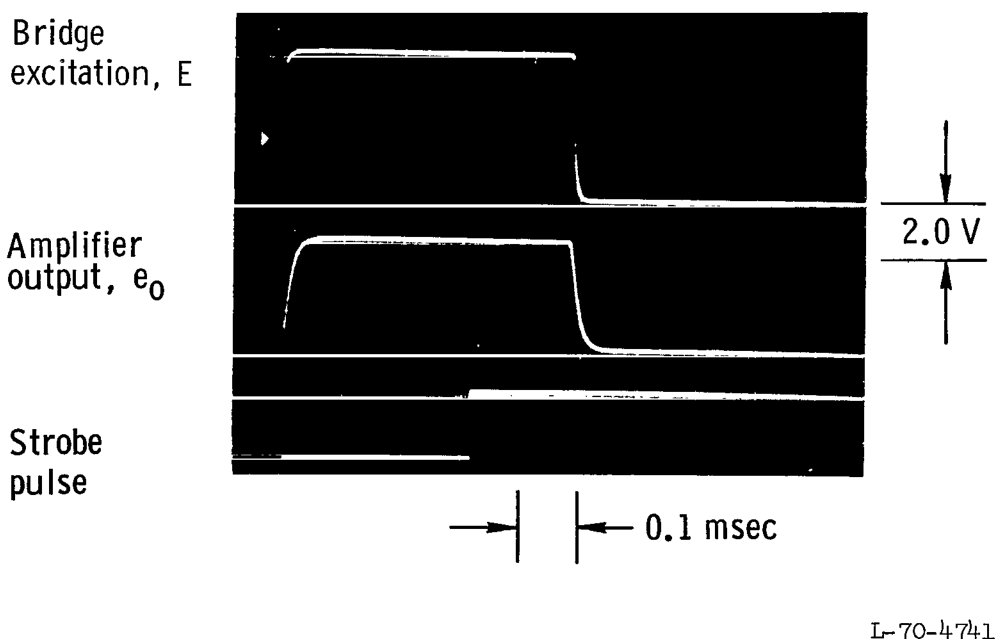


Figure 8.- Timing diagram.

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