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Technical Report 32-1554

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Preface

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory. Louis A. Rosenthal, a consultant to the Jet Propulsion Laboratory, is a professor in the Department of Electrical Engineering, Rutgers University, New Brunswick, New Jersey.

Acknowledgment

The authors would like to acknowledge the assistance of H. Jeffries in preparing electroexplosive devices for testing and in conducting the experiments.

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Abstract

By employing a self-balancing bridge it is possible to ascertain the electrothermal and nonlinear behavior of an electroexplosive device. A sinusoidal current is passed through the device which provides a signal in the form of a unique Lissajous display. This display can be qualitatively evaluated and abnormal units can be readily detected.

Electrothermal Follow Display Apparatus for Electroexplosive Device Testing

I. Introduction

A continuing effort at the Jet Propulsion Laboratory is to provide, at a minimum of expense, high-reliability devices and systems for spacecraft application. In the area of electroexplosive devices (EED) high reliability is most important. Many mission critical functions aboard spacecraft are explosively actuated. To demonstrate by statistical methods and destructive testing the high reliability needed would incur a financial burden. The application of nondestructive testing, in which the behavior disposition of each EED selected for use aboard the spacecraft can be determined, will result in high confidence and reliability. For a more complete evaluation of the EED's to be used, a minimum of destructive testing will be required, leading to cost savings. This paper reports on a technique which will yield valuable insight as to the quality of each EED in an efficient and nondestructive manner.

The electrothermal follow display apparatus is a qualitative inspection tool capable of evaluating the integrity of the electrical bridgewire system and its thermal contact to the explosive material at the bridgewire interface. By means of an oscilloscope display it is possible to rapidly discern deviations from normal behavior. Abnormal displays can in most cases be related to specific faults. The basic electrothermal follow concept will be developed.

Consider a bridgewire-explosive system with a sinusoidal driving current. As current varies from zero to a maximum, the bridgewire heats up but the temperature rise always lags the instantaneous joule heating. This thermal lag is a result of the equivalent heat capacity and heat loss of the system. The temperature excursions "follow" the instantaneous power. A system having no heat capacity or thermal storage equivalent would result in zero follow or an "in phase" thermal response. Heat capacity will always result in a temperature lag or follow.

There is an additional connotation in the use of the term "follow." For the sinusoidal drive current, the ideal bridgewire system voltage drop would exactly follow the current in a simple ohmic manner. Because of the thermal lag previously described and its influence on the resistance due to a temperature coefficient of resistance (TCR or α), the voltage wave does not follow the current wave but manifests a phase lag. In addition to the thermal-time-dependent behavior, there can be an amplitude-sensitive instantaneous distortion in the follow. For example, rectification at a bridgewire junction or voltage breakdown at an oxide interface can produce erratic follow behavior. The basic ideas associated with follow action will be explored.

II. Nonlinearities and Follow Behavior

The more erratic instantaneous nonlinearities will be initially considered. Three hypothetical nonlinearities are shown in Fig. 1. The abscissa is current, the independent variable, and the ordinate is voltage. For each case assume a sinusoidal current excursion. In case (a) of Fig. 1 at some positive current a voltage jump is experienced in the region *a–b*. After *b*, the wire resistance as measured by the slope of the *v–i* characteristic is higher. Conceivably a radial crack in the bridgewire has partially opened owing to wire strains. The unlikely case of asymmetrical behavior for negative currents is shown. Each instant in the current cycle, in passing through this discontinuity, the voltage will "jump" in zero time similar to a switching action.

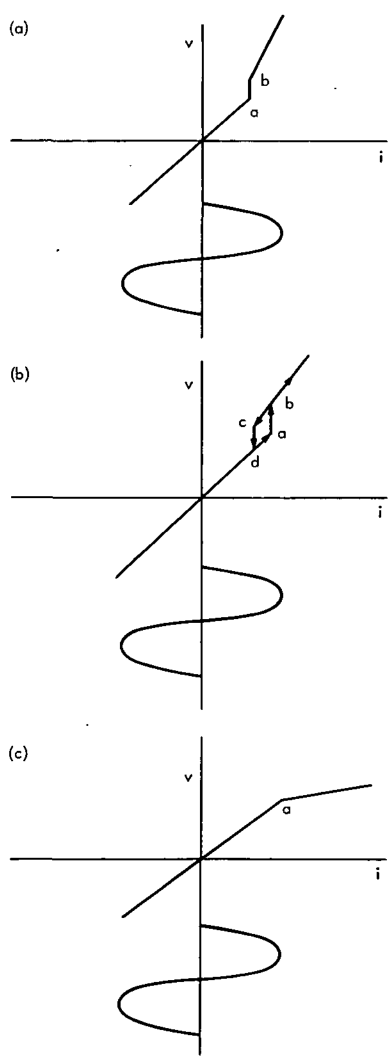


Fig. 1. Assumed instantaneous nonlinearities resulting from a sinusoidal current through the bridgewire

In case (b), double valued behavior is demonstrated. The basic variations experienced in case (a) occur, but in coming down from the positive current maximum the crack remains opened down to level *c* (perhaps due to a thermal lag in strain), whereupon it closes instantaneously to a resistance corresponding to point *d*. Here again it is likely that the same nonlinearity should occur in the third quadrant. Zero point symmetry in any electrothermal follow display is indicative of bilateral behavior or i^2 dependence.

For case (c) there is a resistance decrease at point *a*. Consider a weld joint whose contact resistance is decreased because of wire strains at increasing current. The sharpness of the slope discontinuity at the corner (*a*) would be an indication of the time-dependence of strain.

A wide variety of strange resistance discontinuities can be observed. The details of the fault interpretation have not been investigated. They have been collated with certain transient testing techniques (Refs. 1, 2, and 3) and are mysteriously real. Such erratic nonohmic resistance behavior must be suspect, and the particular item should be culled out in any high-reliability sorting procedure.

Thermal nonlinearities are more analytic and provide the normal type of thermal follow response. If a sinusoidal current

$$i = I \sin \omega t$$

is passed through an electrothermal system, there will be a double-frequency (2ω) power variation and a corresponding temperature excursion at some lagging angle. Providing there is some TCR, a resistance modulation (Refs. 4 and 5) is produced according to

$$R(t) = R_B \left[1 - m \cos (2\omega t - \beta)\right] \qquad (1)$$

where R_B is the average hot resistance, m describes a degree of modulation, and β is a phase angle according to

$$\beta = \tan^{-1} 2\omega \frac{C_P}{\gamma} \qquad (2)$$

$C_P/\gamma = \tau$, the thermal time constant of the system, where C_P is the lumped heat capacity of the system and γ is the heat loss. The resistance modulation term is complex (Ref. 6) and derived as

$$m = \frac{\alpha I^2 R_B}{2\gamma\sqrt{1 + (2\omega\tau)^2}} \qquad (3)$$

The per-unit resistance is directly dependent on the power level and the TCR, but inversely related to the heat loss and a frequency-sensitivity function.

The instantaneous voltage drop across the device is $v(t)$, where

$$v(t) = i(t)\,R(t) \tag{4}$$

For a given device and power level, the modulation term m is a constant resulting in

$$v(t) = R_B I\,[1 - m\cos(2\omega t - \beta)]\sin\omega t \tag{4a}$$

The voltage drop $v(t)$ contains a fundamental (ω) component at some lagging phase angle with the current waveform and, in addition, a third harmonic again at some phase angle. It is sufficient to indicate that

$$v(t) = V_1 \sin(\omega t - \phi_1) + V_3 \sin(3\omega t - \phi_3) \tag{4b}$$

where V_1 and V_3 are the component amplitudes.

A technique wherein the fundamental component is cancelled out in magnitude and phase angle in a bridge circuit, leaving only the third harmonic, has been employed to measure m and relate it to the electrothermal parameters (Ref. 7). It will be shown that the display apparatus presented here operates by partially cancelling out the fundamental using self-balancing bridge action.

Figure 2a is an exaggerated volt-ampere trace for an electrothermal nonlinearity. It is properly referred to as a Lissajous display, wherein the current and voltage are periodic time functions. At the origin, both the current and voltage are zero, and as current varies cyclically, the arrows indicate the trajectory. Resistance, as measured by the slope, is lowest at the start of the cycle. Sometime after the current peak, the voltage peak follows. There is no unilateral action; hence the first and third quadrants are identical. The Lissajous trace is an instantaneous plot of Eq. (4a), the ordinate, combined with

$$i = I\sin\omega t$$

the abscissa. If the fundamental was completely cancelled from the ordinate display (by some auxiliary balancing scheme) the display would be that shown in Fig. 2b. This display is a result of a fundamental (H, horizontal deflection) and a third harmonic (V, vertical deflection) with some phase shift.

If the phase angle of the third harmonic (or the fundamental) is shifted by some auxiliary means, Fig. 2c is obtained and a Lissajous result of $V_3 \sin 3\omega t$ and $I \sin \omega t$. It should be noted that the true element $v - i$ characteristic must pass through the origin ($v = 0$ at $i = 0$) and the trace of Fig. 2b could only be obtained by artificially shifting the phase angle between the device voltage and current by employing a reactance in one bridge arm.

If the voltage drop across the device has a major portion but not all of the fundamental component removed, thus exaggerating the nonlinearity, a dynamic $v - i$ trace as is shown in Fig. 3a is obtained. The arrows indicate the heating cycle, and for a particular current two voltage drops are possible. A lower drop corresponds to the increase in current with the temperature rise or resistance lagging. The down portion of the current cycle finds the wire hot and the corresponding voltage drop higher. This typical trace is obtained in the electrothermal follow apparatus where the horizontal is a sine-wave current excitation and the vertical is a fundamental with a third harmonic component.

All of the wave shapes or displays described have been generated by combinations of sine waves. Since heating follows the instantaneous current squared, the dynamic $v - i$ traces are waveform-dependent. Consider square-wave excitation (current) of an electrothermal device. If the current I is symmetrical, the display is a straight line of slope R_B. There is no change in the heating cycle since $I^2 = (-I)^2$. When the current goes from 0 to $+I$ and then returns to 0, the display is shown in Fig. 3b. Heating takes place from a to b while cooling is at the origin. It is possible to rotate or shift the $v(t)$ display so that it extends below the axis (i.e., negatively) by simply subtracting a linear voltage proportional to the current waveshape.

Combinations of instantaneous and thermally dependent nonlinearities result in more complex displays and can often be recognized in light of the previous discussions. All electrothermal nonlinearities are frequency-dependent, since at high frequencies there is no follow and m approaches zero. Therefore, in seeking the nonlinearity an appropriate frequency of current drive must be chosen compatible with the thermal time constant, the electronics, and display circuitry required.

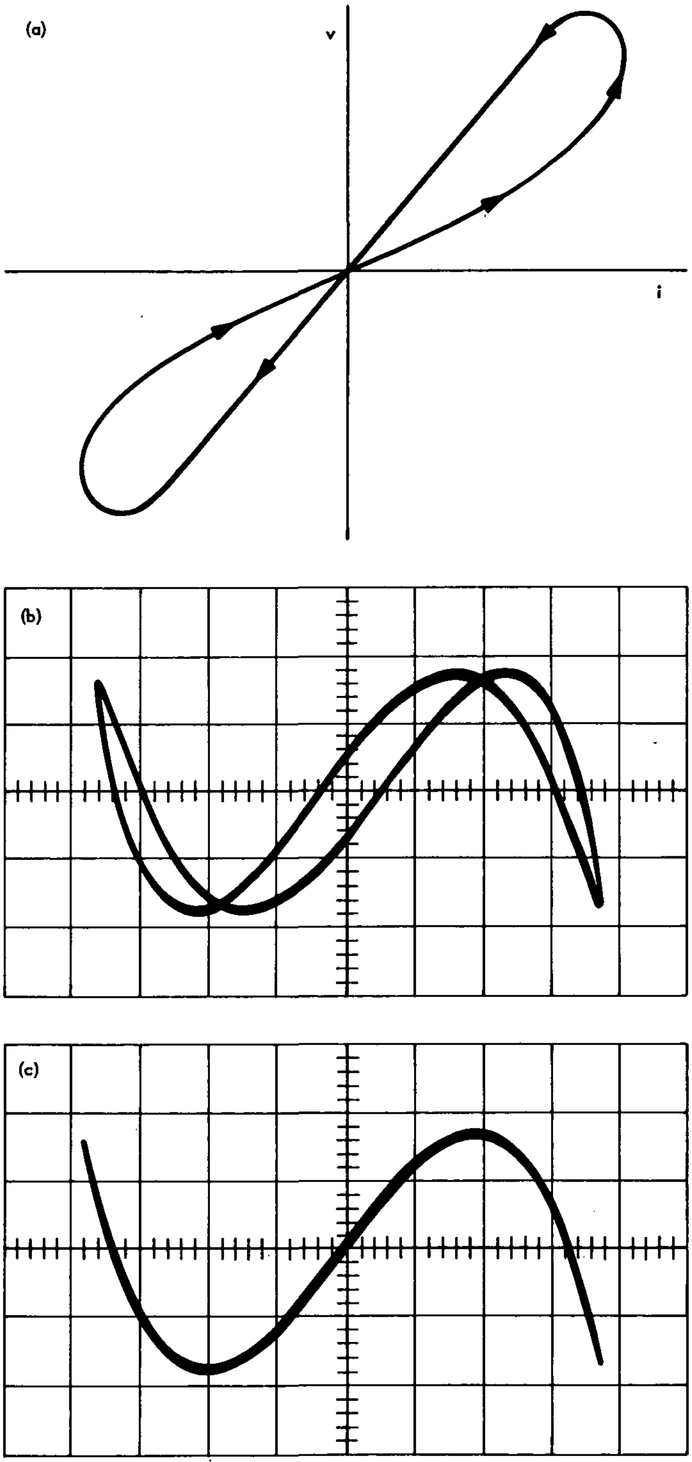


Fig. 2. Electrothermal nonlinearities: (a) result of thermal feedback influencing the resistance; (b and c) exaggerated nonlinear traces resulting from removing the linear component

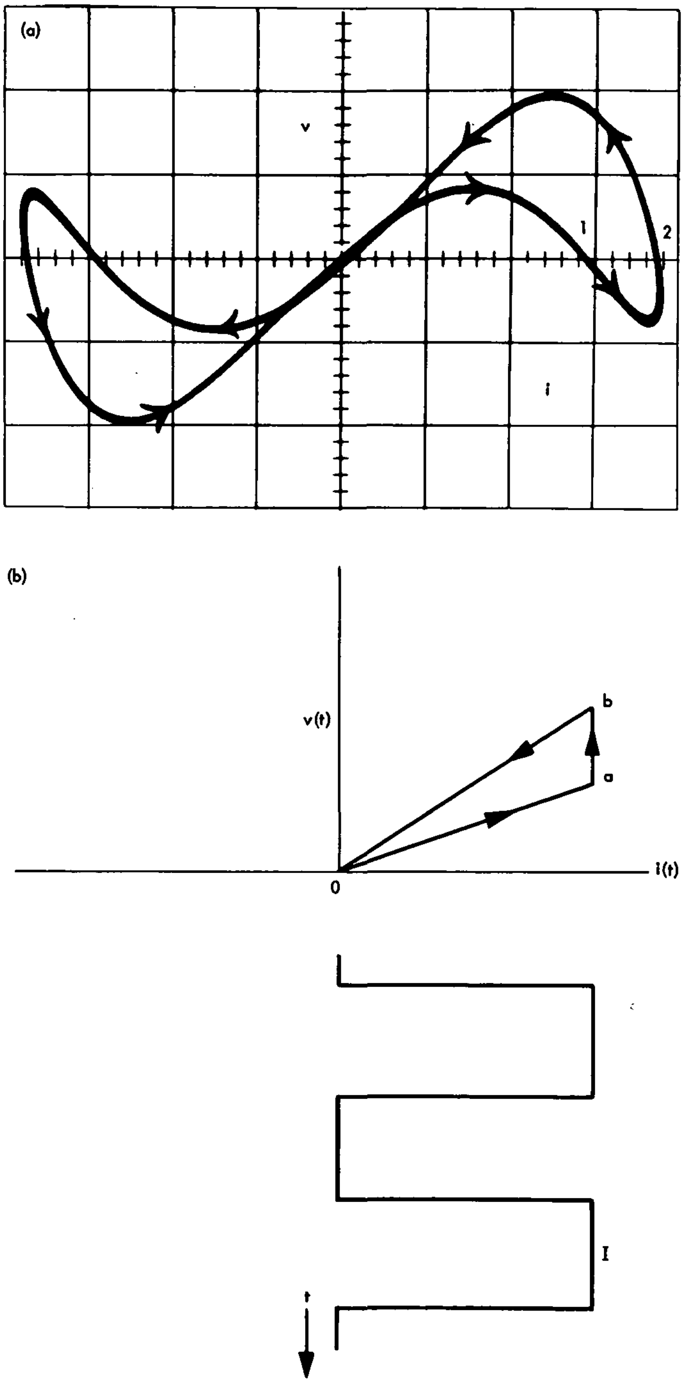


Fig. 3. Thermal follow displays: (a) time lag nonlinearity; (b) waveform sensitivity as demonstrated by the square-wave current drive

III. Self-Balancing Bridge Action

A technique based on the use of a self-balancing bridge to generate a sinusoidal current and a meaningful display has been developed. It is, however, possible to obtain the displays with a manually balanced bridge. Consider Fig. 4a, which is a simple Wheatstone bridge with the electroexplosive device as the electrothermal nonlinear arm R_B. Select R_2 large compared to R_B (10:1) so that the current through R_B is independent of the resistance modulation. The voltage drop across R_B is v_t and contains the fundamental and third harmonic according to Eq. (4b). The adjacent arm (R_1) has a voltage drop which is a replica of the applied voltage (v_a) or the current through R_B. Note that the error voltage v_e follows:

$$v_e = v_t - v_1 \tag{5}$$

and it is possible to balance out various amounts of the fundamental component ($\sin \omega t$) by an adjustment of V_1. Note that it is impossible to null out v_e to zero since the R_B arm internally generates a third harmonic and out-of-phase component of voltage. The two components of the voltage v_t can be shown (Ref. 6) to be

$$v_{t1} = IR_B \left[\sin \omega t + \frac{m}{2} \sin (\omega t - \beta) \right] \tag{6}$$

and

$$v_{t3} = -IR_B \left[\frac{m}{2} \sin (3\omega t - \beta) \right] \tag{7}$$

By setting the level of v_1 to cancel out the total $\sin \omega t$ component of Eq. (6) by a manual balancing procedure, the error voltage is

$$v_e = \frac{IR_B\, m}{2} \left[-\sin \beta \cos \omega t - \sin (3\omega t - \beta) \right] \tag{8}$$

This is the ultimate balance condition, and the error contains a residual fundamental and a lagging third harmonic. Note that at $\omega t = 0$, $v_e = 0$ or the error voltage passes through the origin at $v_a = 0$.

If v_e is made a vertical oscilloscope deflection while v_a is made the horizontal deflection (proportional to the current $I \sin \omega t$), the display is the typical electrothermal nonlinearity trace as seen in Fig. 3a. Equation (8) indicates two zero crossings in the first half cycle of current drive ($0 < \omega t < \pi$) at the points indicated as 1 and 2 in Fig. 3a. If there is no thermal lag but complete follow, $\beta = 0$ and a single zero crossing results corresponding to

$$\sin 3\omega t_1 = 0 \tag{9}$$

For a high lag system (i.e., large thermal time constant or $\beta \rightarrow \pi/2$) the zero crossings are determined by

$$\cos \omega t_1 = -\cos 3\omega t_1 \tag{10}$$

The degree of lag is related to frequency and thermal time constant τ according to

$$\beta = \tan^{-1} 2\omega\tau \tag{2}$$

A self-balancing bridge (Ref. 8) can automatically bring the bridge of Fig. 4a to a near balance condition. Figure 4b employs the nonlinear bridge as a regenerative

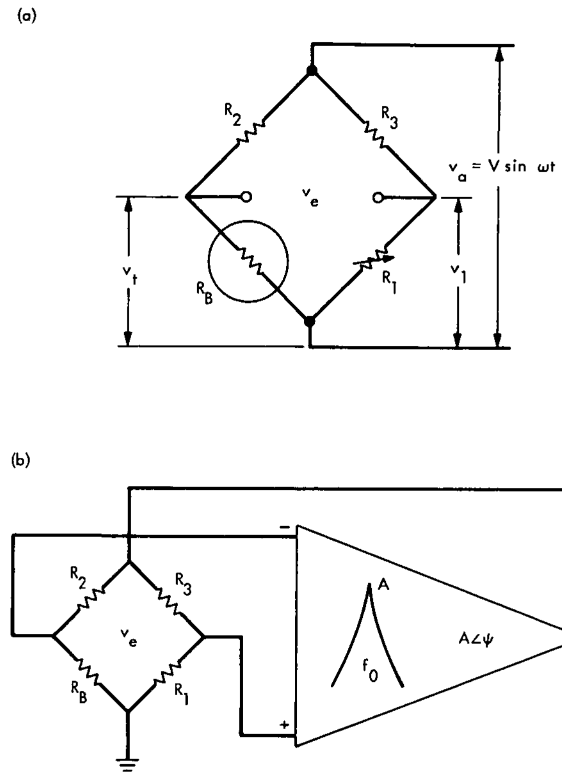


Fig. 4. Wheatstone bridge with regenerative feedback loop: (a) bridge can be manually balanced to yield a residual error voltage due to harmonic generation and phase shift in the R_B arm; (b) self-balancing action can be achieved, leaving the dominant nonlinear behavior as the error voltage

feedback loop for the selective power amplifier A. If upon closing the loop the bridge is unbalanced so that

$$\frac{R_B}{R_B + R_2} < \frac{R_1}{R_1 + R_3} \tag{11}$$

regeneration or positive feedback will take place, resulting in a growing sinusoidal oscillation. Since the amplifier is selective, only one frequency will appear in the output v_a, the power source for the bridge. As the oscillation grows, the average power dissipation in R_B, the only thermally sensitive arm, results in the bridge approaching balance, reducing the feedback and establishing oscillation equilibrium. This condition corresponds to

$$\frac{v_a}{v_e} = A\angle\psi \tag{12}$$

The amplifier gain has magnitude A and phase angle ψ. As the gain approaches infinity, the bridge is brought closer to balance. A complete balance condition is never attainable since there would be no feedback to the amplifier. Thus, the self-balancing action is never perfect owing to the finite gain, but as an approximation R_B approaches, but never equals, R_1R_2/R_3 (i.e., $R_B < R_1R_2/R_3$).

Although the average value of R_B is always less than the balance condition, the instantaneous resistance exhibits dynamic excursions about the balance point. By selecting a low frequency for the selective amplifier (i.e., $f_0 = 10$ Hz), the desired nonlinear thermal follow can be extracted at the bridge error points. A display of v_e vs v_a contains the electrothermal nonlinearity information desired. High selectivity and high gain are essential to reduce the fundamental bridge error voltage v_{e1} to near zero. Under these conditions only the third harmonic and an out-of-phase component of the fundamental appear at v_e, providing the electrothermal nonlinearity signal.

By making R_1 variable it is possible to control the amplitude of current drive ($I \sin \omega t$). For example, if by setting R_1 low, R_B is initially

$$R_B > \frac{R_1 R_2}{R_3} \tag{13}$$

oscillation will never commence; the feedback is entirely degenerative. Increasing R_1 will result in a "break-in" to oscillation. This value of R_1 relates to the cold resistance of R_B according to

$$R_B = \frac{R_1 R_2}{R_3} \tag{14}$$

at break-in. Setting the value of R_1 higher will call for an increase in the average value of R_B. This can only be accomplished by a larger amplitude of oscillation and as increased power dissipation in R_B.

Whereas manual balance can result in complete cancellation of the fundamental in-phase resistance modulation term, a sufficiently close to balance condition can result with the self-balancing system. There will, however, always be a residual signal, most obvious when temperature excursions are small ($m \to 0$).

IV. The Apparatus

The circuit diagram of Fig. 5 is the apparatus developed to provide electrothermal follow displays. A purely resistive bridge includes the electroexplosive device as an electrothermal nonlinear component. All other arms are selected to be thermally insensitive. The 10-Ω (R_2) arm produces the current drive in the device due to the bridge voltage v_a. Sensing the voltage as the horizontal component of the display is equivalent to sensing the current since

$$i = \frac{v_a}{R_2 + R_B}$$

The comparison arm is adjustable and a 0–1 kΩ Helipot is equivalent to a set point of 0–2 Ω (for R_B, the adjustable arm). This bridge has been designed for nominal 1-W/1-A no-fire electroexplosive devices having a 1-Ω resistance typically employed in the aerospace industries.

The bridge error voltage in a balanced manner is detected by the operational amplifier A_1 operating with a gain of 10. Capacitors C_1 and C_2 are necessary to control high-frequency rolloff, and at 9.6 Hz, the exact operating frequency, no phase shift is observed. The output of this amplifier provides the bridge error voltage amplified by 10 and is the vertical portion of the follow display. To continue with the self-balancing circuit, amplifier A_2 operating with a parallel "T" null network selective amplifier yields another gain of 60 with a selectivity primarily limited by the accuracy of the tuning components ($R_5 - C_4$). A measured Q of 17 at a frequency of 9.6 Hz was practically attained in this stage.

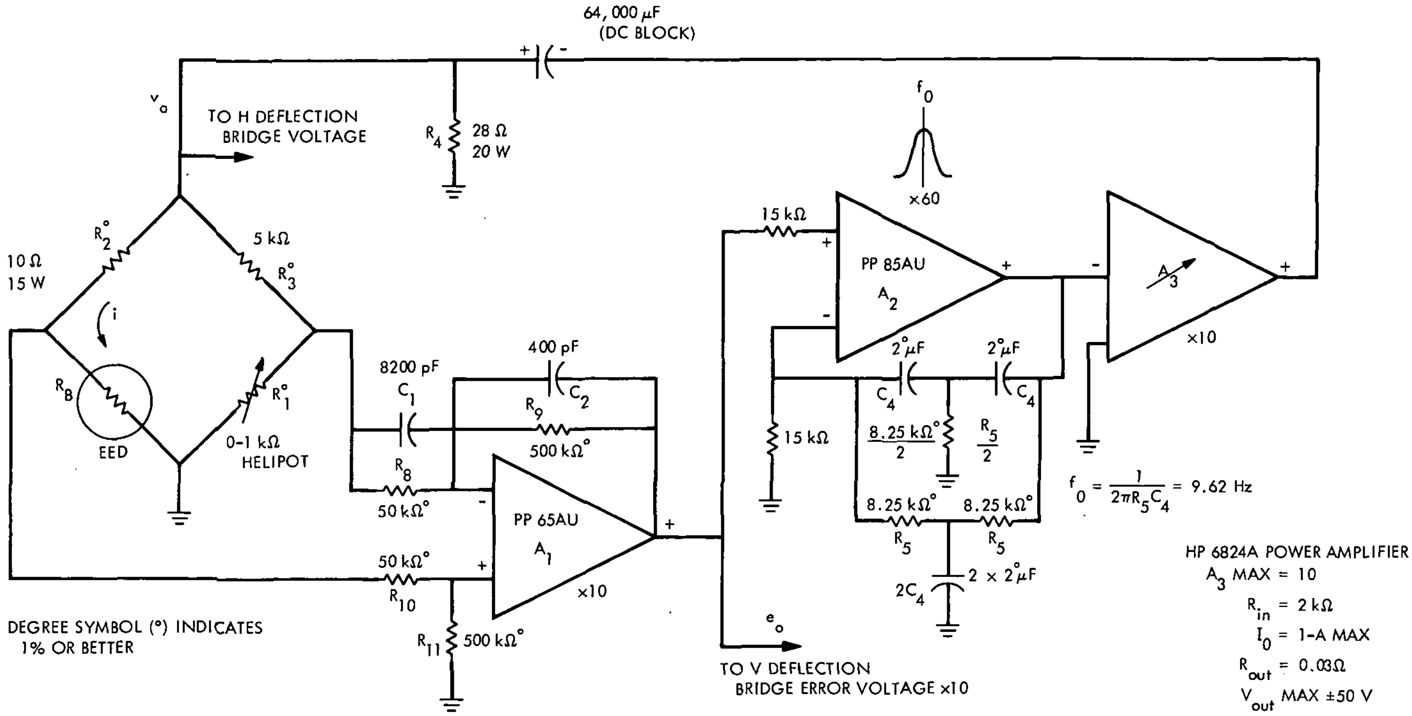


Fig. 5. Complete circuit diagram of the electrothermal follow apparatus

Note that both the A_1 and A_2 stages operate at low signal levels and any general-purpose operational amplifiers are satisfactory. The power output stage A_3 is a commercial (HP 6824A) power amplifier stage with an adjustable gain of 0 to 10. This amplifier is output-current-limited to ± 1 A peak and has sufficient capacity to produce 1/2 W dissipation in the EED ($i_{rms} = I_{max}/\sqrt{2}$). As an additional safeguard, by shunting the bridge with R_4 (28 Ω) it is possible to divert 28% (11/39) of the current and limit the power to approximately 1/4 W.

The need for sufficient power capability at the output of A_3 is related to the power sensitivity of the electroexplosive device under test. A typical insensitive electroexplosive device employing Tophet "A" wire ($\alpha = 100 \times 10^{-6}$) would have a γ/α of 20 W. This means that 20 W will double the resistance due to electrothermal response. One watt would increase the resistance by only 5% and 200 mW would increase the resistance by 1% (i.e., 100°C). For 200 mW of dissipation the EED current would be 0.45 A rms (0.635 peak) and the bridge voltage would be 4.95 V rms (7.0 V peak). The resistance resolution in potentiometer R_1 must be fine so that continuous level adjustments can be made.

For a typical unit, self-oscillation would start when the set point was equivalent to 1.018 Ω. A 5-V (peak) bridge voltage was observed for 1.032 Ω, a resistance increase of 0.014 Ω (or 1.4%). A unit with large γ/α requires large power changes for small "called for" resistance changes. The bridge voltage v_a is a perfect sine wave as long as amplifier A_3 is within its dynamic limits and power changes can easily be measured.

The entire system is dc-coupled except for a feedback capacitor C_3. It was not possible to dc-balance A_3, and if dc were injected into the bridge circuit certain prominent second harmonics or asymmetries would be introduced into the display. No meaningful phase shift could be observed at 10 Hz, and the capacitor C_3 precludes the need for careful dc balance. Other variations of the selective amplifier design are possible, but high loop gain is of paramount importance. For example, with the maximum gain of 6000, a 1-mW error signal would put 6 V across the bridge at v_a. This is the typical degree of balance obtained, and R_B (at 1 Ω) would be 0.2% below the set point based on R_1. By installing a precision resistor for R_B, the basic bridge accuracy can be established by checking the break-in point.

The operating procedure is very simple. When the R_B terminals are shorted the oscillation ceases and the EED can be inserted or removed without danger of accidental firing. Rheostat R_1 should be set below the cold resistance point for R_B. Upon removal of the short, the circuit remains in a stable "off" condition. As R_1 is increased, calling for higher operating resistance in R_B, a break-in point is reached where a low level of oscillation commences. This resistance is essentially the cold resistance for the device; when the set point is increased, the EED is forced to increase its resistance by a power dissipation mechanism previously described. A typical set point would result in a $\pm$7-V swing across the bridge as measured by the horizontal scope display. As a point of interest the per-unit change in resistance to go from the break-in point to a fixed level (i.e., $\pm$7 V) of power is relatable to the γ or heat loss factor for the item.

With the buildup of v_a, there is a corresponding buildup of the error voltage e_0, and the Lissajous display as presented on a dc-coupled oscilloscope is the follow trace. Note that the error voltage is increased by the gain of A_1. Typical amplitudes of $\pm$20 mV ($\pm$2 mV at the bridge) are obtained, with the major portion being the third harmonic component due to electrothermal follow.

Some observed results will be presented with qualitative interpretation. Since the error is displayed after passing through A_1, a 180-deg phase reversal of the error and follow display is present. Certain scopes have the facility to correct this inversion.

V. Observations

A series of electrothermal follow traces depicting some normal, abnormal, and experimental traces as obtained with the apparatus shown will demonstrate the application. Figure 6a shows a follow trace where the nonlinearity is totally voltage-dependent (Refs. 9 and 10). A nonlinear silicon carbide resistor (Thyrite) was placed across the R_2 arm (Fig. 5) to inject a slight degree of nonlinearity. Silicon carbide decreases its resistance with voltage as opposed to a thermally responsive positive TCR device; hence the bridge arm location was changed. The EED was replaced with a 1-Ω precision resistor. Oscillation break-in took place at 1.01 Ω with a maximum loop gain of 6000, and the observed trace was at a set point of 1.042 Ω. Because there is no thermal follow or lag, the trace has no area (i.e., it is single-valued), except for a trivial phase shift. The trace is a result of sinusoidal abscissa and a vertical signal which includes sin ωt and sin $3\omega t$ terms. If the vertical sin ωt component were completely cancelled out by an infinite gain self-balancing bridge, the figure would rotate counterclockwise and give a perfect cubic display.

In Fig. 6b the influence of a thermal environment for an experimental system is demonstrated. A plastic squib header (MK1 squib) employing a platinum bridgewire 0.0254 mm (1 mil) in diameter by 2.54 mm (100 mil) in length was set for a nominal resistance of 1.086 Ω. The small inner trace obtained is indicative of a high degree of thermal lag (a long thermal time constant) for this bare bridgewire system. Upon surrounding the wire with a liquid coolant (alcohol), 9 times as much power or 3 times as much current was required to keep the resistance the same 1.086 Ω. The coolant has reduced the thermal time constant, resulting in less lag and a higher magnitude of follow. This is the typical effect of surrounding a bridgewire with an explosive mix.

In Fig. 7, three normal traces are shown for typical spacecraft EED's. Items displayed in Figs. 7a and 7b are those of one manufacture; Fig. 7c displays an item of another. By other testing techniques the item displayed in Fig. 7c has a larger τ and smaller γ than the first two items. Note that all items are tested at the same power level, as indicated by the horizontal deflection. It would be no problem to pick out differences in electrothermal behavior from the traces presented. Although there are electrothermal differences, all units are completely satisfactory. A manufacturer in comparing items (a) and (b) in a production line might question the differences and review his process control. To repeat a point of interest, if the fundamental in the error signal could be completely removed, the figure would rotate counterclockwise.

Normal traces in Fig. 8 show the influence of ambient temperature on the follow trace for a typical aerospace EED. In Fig. 8a the item is in a liquid nitrogen environment. Figure 8b is the room temperature case; Fig. 8c corresponds to 100°C above ambient. Note that for the trace in Fig. 8a the vertical sensitivity is 4 times that of the two following cases. At the subnormal temperatures, there are large lag and large temperature excursions. The heating current is the same for all cases, and the wire temperature extremes depend on the hot and cold limits. Going from (b) to (c) the temperature excursions decrease, indicating that in the hottest case, (c), heat flow from the wire out and in is the least. The lowest γ was observed for the lowest temperature, and this is in contradiction to the concept that heat flow or loss (i.e., γ) depends on the temperature differential. Based on other experiences, it is conceivable that the explosive mix has lost thermal contact with the wire in case (a).

Figure 9 includes an abnormal follow trace. Note the discontinuity which develops at the higher current levels, as though the resistance suddenly increased. The trace is reproducible and repetitive at 10 displays per second and can be a result of some weld joint malfunction. A detailed study of the wide variety of abnormal traces has not been made, but it is known that nonohmic welds can produce such traces. In Fig. 9b, transient testing techniques show similar resistance jumps. In transient testing methods (Refs. 1, 2, and 3), a current step is injected into the bridgewire system and the resistance excursion is tracked. Normally, for a healthy EED a smooth, simple exponential heating curve is observed. In all cases, electrothermal follow trace abnormalities were duplicated by transient testing techniques.

Additional abnormal traces are shown in Fig. 10. In case (a) there is no thermal response until higher currents are attained. For case (b), each successive cycle resulted in a slightly different trace, indicating progressive failure or healing. Case (c) is another unusual and unexplainable abnormal response. Rectification or unilateral displays are rarely seen in stable reproducible traces. Although the abnormal unit will probably initiate if called upon to do so at this time, it must be treated as suspect. Certainly in the case of high reliability units these abnormalities cannot be trusted, for they may, with time, actively progress to a failure. It should be noted that in the thousands of units tested normal behavior generally prevails. It is suspected that abnormalities occur in bunches, during a production run, resulting from manufacturing adjustments or changes in equipment due to wear or operator failure.

VI. Application

The obvious application of the electrothermal display apparatus is in the checking of normal proper manufacturing techniques. Various stages can be checked during production prior to the completion of the item. Although the electrothermal interface alone is checked, this is a critical region for electroexplosive functioning. The lack of quantitative information is offset by the speed of the test. A standard display templet or overlay can be placed on the oscilloscope face to assist in the interpretation. A sample inspection can be used if high reliability (individual testing) is not justifiable. As a nondestructive inspection tool for EED fabrication, many applications can be envisioned for the technique.

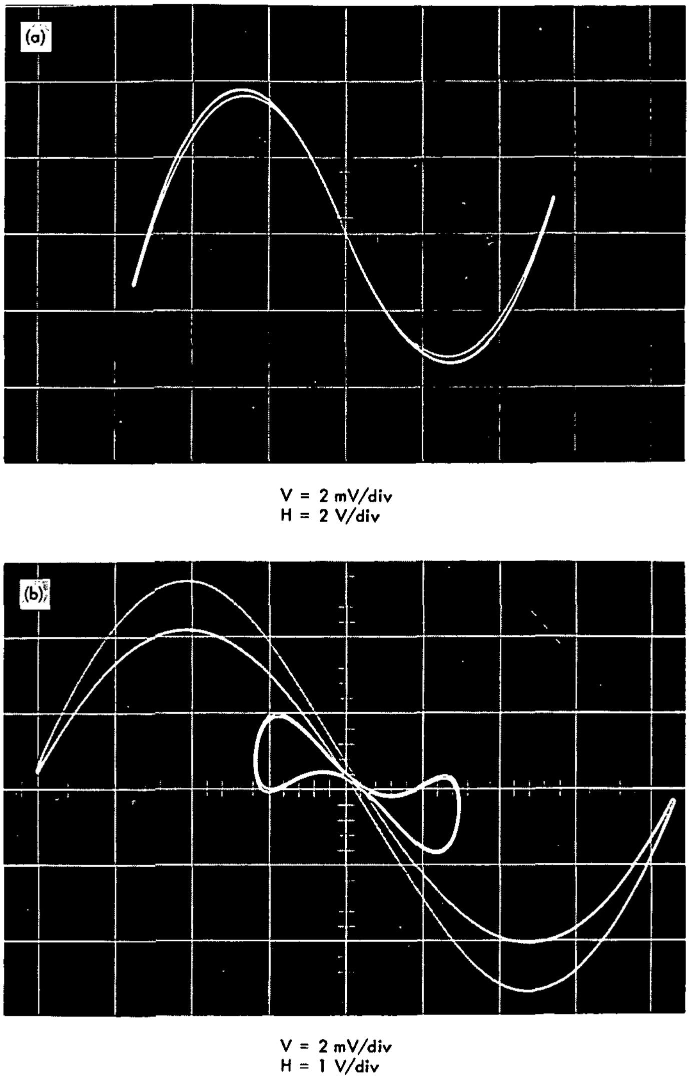


Fig. 6. Electrothermal follow traces: (a) follow trace due to an instantaneous voltage nonlinearity resulting in a zero area trace; (b) drastic change in electrothermal follow trace due to loading a bridgewire system with a thermally conducting environment

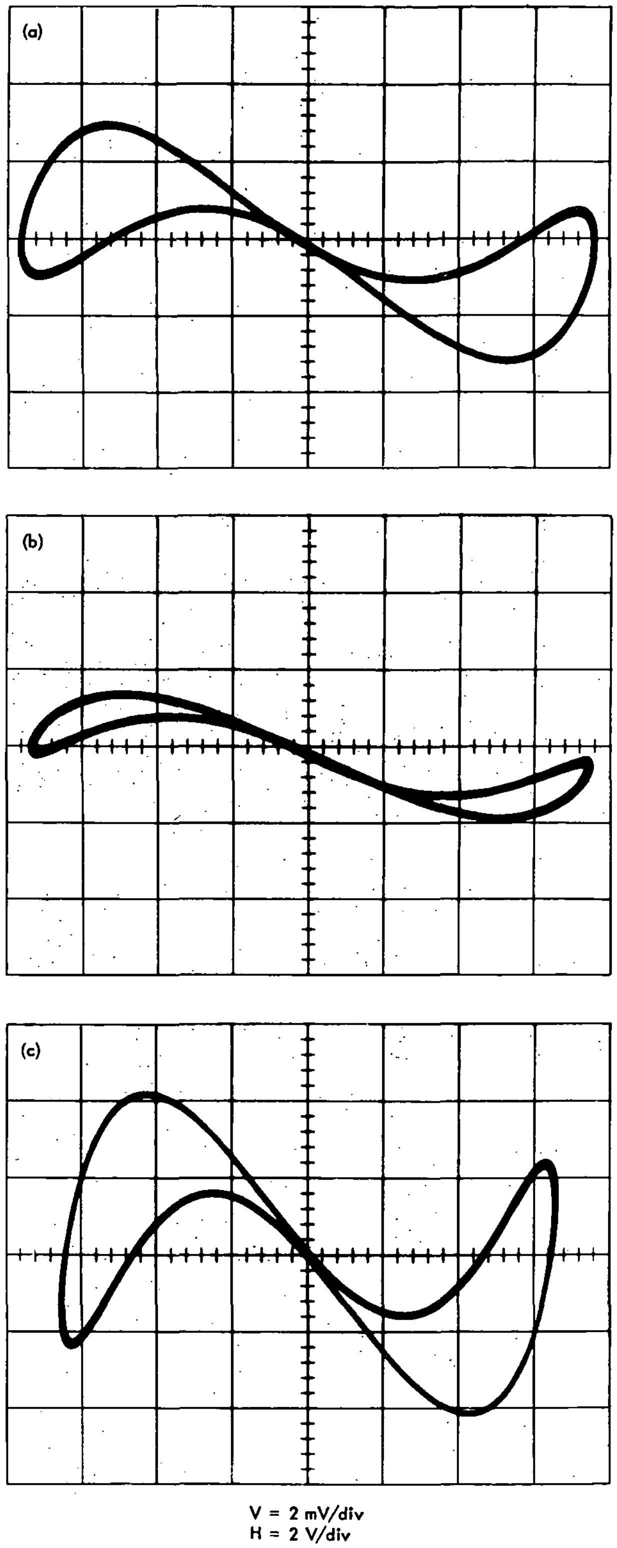


Fig. 7. Typical normal electrothermal follow traces for (1-W/1-A no-fire) aerospace-type electroexplosive devices

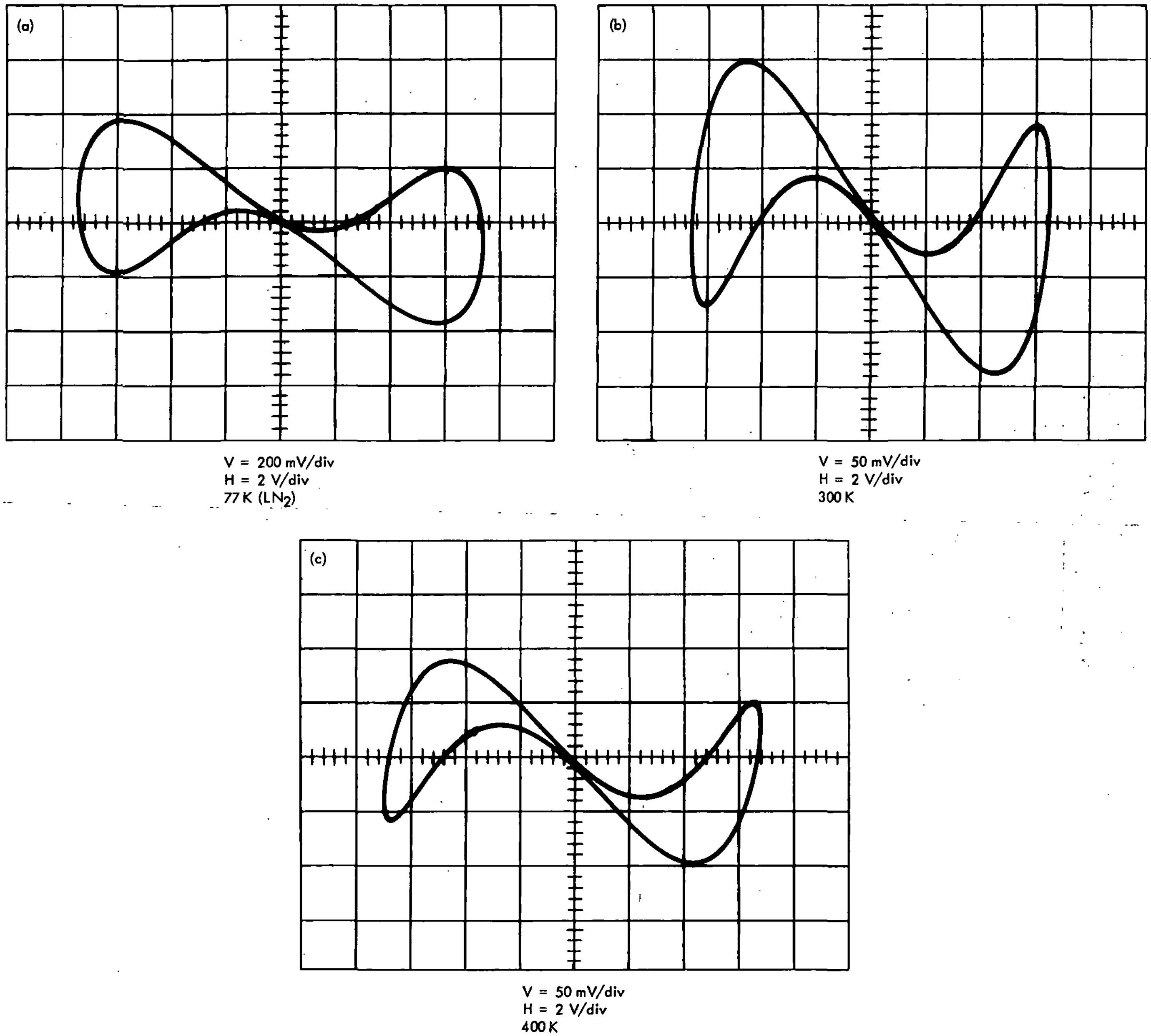
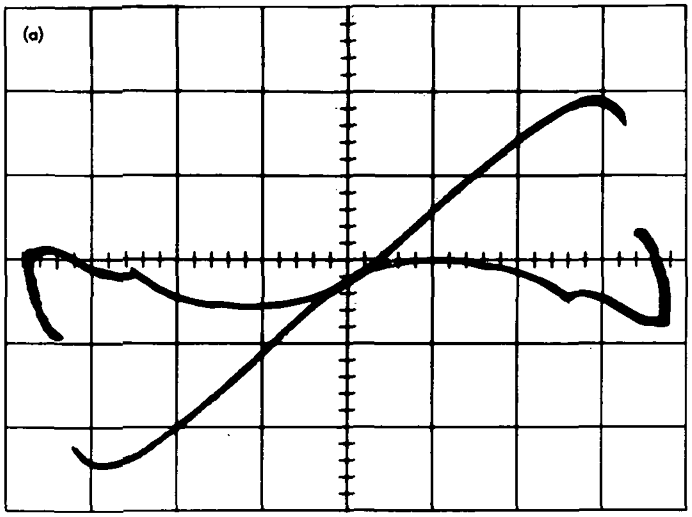
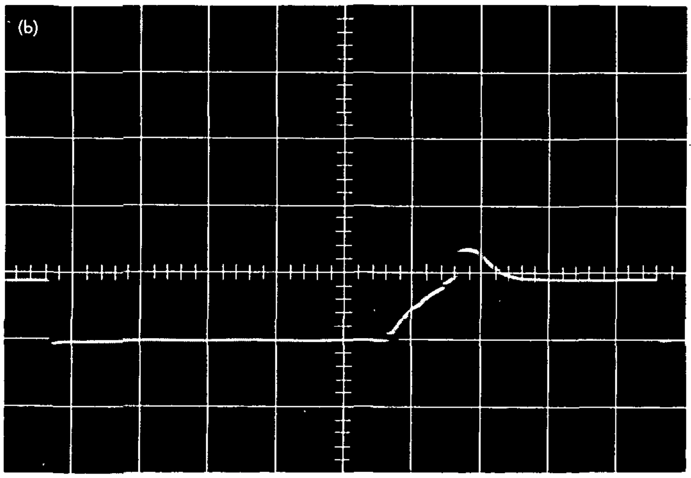


Fig. 8. Electrothermal follow traces for an electroexplosive device at three external temperatures

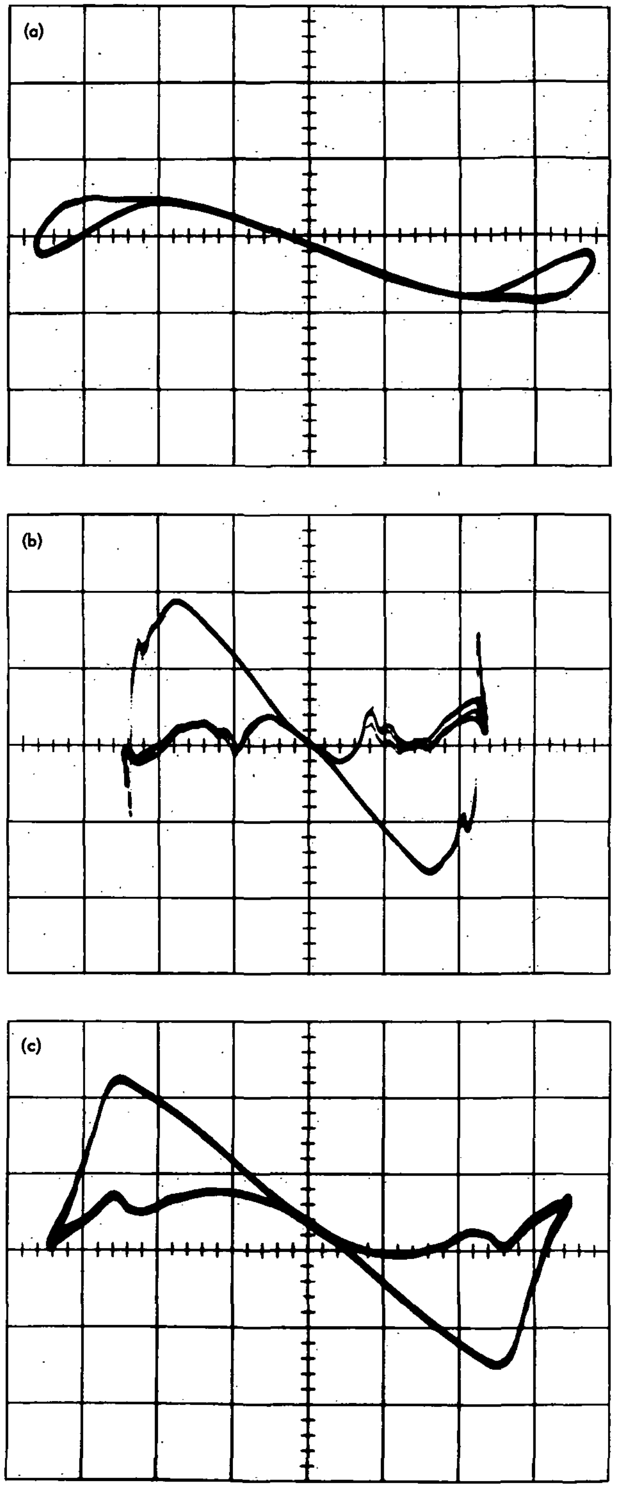


V = [illegible] mV/div
H = 2 V/div



V = 5 mV/div
H = 10 ms/div

Fig. 9. Abnormal thermal traces for an electroexplosive device: (a) electrothermal follow test response; (b) transient pulse test response



V = 2 V/div
H = 20 mV/div

Fig. 10. Abnormal electrothermal follow traces

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