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A STRAIN-GAGE SIGNAL-CONDITIONING SYSTEM FOR USE IN THE LCP*

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Summary

A strain-gage signal-conditioning system, providing wide-band noise rejection and isolation from high voltages that occur during emergency coil discharges, has been developed and tested. The multichannel system combines double-shielded transformers, neutralizing networks, and bandpass filters (with commercial 3-kHz carrier amplifier modules to isolate the strain gages to 5000 V) eliminate thermoelectric effects, and provide a signal bandwidth of 200 Hz. Common-mode interference occurs primarily as a result of "beat-note" effects between the carrier and the superimposed noise at frequencies near the odd harmonics of the carrier. The common-mode rejection of the test circuit was measured to be 120 dB for noise at 2750 and 3250 Hz, 135 dB at 3 kHz, and 135 dB and better at the odd harmonics of 9 kHz and above. The system has been successfully used in strain measurements on the toroidal field coils of the ISX-B tokamak and will be used in the Large Coil Test Facility to monitor strains in the energized coil conductors.

Introduction

Approximately 50 strain gages per coil will be installed in the large superconducting coils that will be tested in the Large Coil Test Facility (LCTF) at Oak Ridge National Laboratory (ORNL). Of these gages, approximately 20 per coil will be installed directly on the conductor in the windings. In addition, approximately 100 strain gages will be installed on the bucking post at the center of the toroidal array and on the intercoil support structure. All of the gages will be at or near 4.2 K after cooldown of the facility. The lead wires for all of the gages will be brought out through vacuum to feedthroughs mounted in flanges on the vacuum vessel wall. During coil testing, the gages will be subjected to magnetic fields of up to 8 T. In later testing stages, the gages and associated leads will also be subjected to pulsed magnetic fields of up to 0.15 T/sec. Additional rapidly changing fields are present during an emergency coil discharge, when the test coil field decreases at a rate of up to 0.1 T/sec. During an emergency discharge, the conductor potential above ground may be as high as 2500 V.

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Environmental Considerations

Magnetic Fields

Magnetic fields can become a major source of errors for strain measurements if adequate precautions are not taken. The magnetic effects with which we are primarily concerned are as follows:

Inductive effects. Even with the use of small, tightly twisted lead wires, the voltages induced by the time-varying magnetic fields in the LCTF, with their large spatial gradients, may be of the same order of magnitude as the strain signals themselves.

Magnetoresistance. The resistance of a given gage will, in general, change when it is place in a magnetic field. A resistance change under these circumstances is indistinguishable from one that is caused by changes in strain in the gage substrate. If a full- or half-bridge gage circuit is used, the effect can be considerably reduced,[1] provided that the entire gage assembly is subjected to the same field. However, magnetoresistance can produce significant errors in quarter-bridge circuits (one active gage), which will be required in a number of locations in the Large Coil Program (LCP).

Thermal Effects

Thermal effects can be another source of error voltages. The more significant of these effects are as follows:

Thermoelectric voltages. In the LCTF, leads are routed from gaged at liquid helium temperature through vacuum to feed throughs at ambient temperature. The sharp temperature gradients incountered at this interface can produce unwanted dc voltage due to thermoelectric effects. When strain-gage systems are operated in a direct-current mode, these thermoelectric voltages can represent significant errors. Systems that employ ac carrier excitation and phase-sensitive signal conditioning are not subject to these errors.

Apparent Strain-vs-Temperature Effects

Gage-alloy resistivity variation with temperature and differential thermal contraction effects between gage and substrate result in gage resistance changes when the temperature is varied, even when the substrate is unstrained. These effects are independent of the type of signal conditioning used. Self-temperature-compensating gages can be used over limited temperature ranges to reduce the effect, but such compensation is not available for the entire temperature range of LCTF (4-300 K).

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High Voltage Excursions

Because strain gages require very close mechanical coupling to their substrates, in general, their insulation must be very thin; therefore, they can withstand only low voltages. The high voltage of the coil conductor during the emergency coil discharge thus poses operational and safety problems for gages mounted on the coil conductors.

Electrical Noise

The LCP coils will be energized by high-current, low-voltage, SCR power supplies, which are notorious for the generation of high-frequency electrical noise. Although our power supply specification limits all ripple between 2 Hz and 100 MHz to a level of 500 mV or less, this level of noise is significant as compared to the low-level signal voltages from strain gages mounted on conductors. Furthermore, it may be possible for high-frequency standing waves to exist within the coil, and these could have peak noise potentials well above the limits established at the power supply terminals.[2] Finally, there will be the noise at 60 Hz and its harmonics associated with the high-current ac power lines, motors, and transformers in LCTF.

Signal-Conditioning Methods

Direct-Current Operation

Over the past ten years, dc strain-gage signal conditioning systems have become dominant because of their simplicity, ease of operation, and relatively low cost as compared with as systems. However, dc systems are incapable of rejecting thermoelectric voltages. Low-pass filters can be used with dc systems to remove noise with frequencies above the signal bandwidth, but cannot be used to filter out noise in the desired signal bandwidth (in LCTF, 0-100 Hz) without filtering out the signal itself.

Alternating-Current Operation

To produce reliable results,[3] before the development of highly stable dc amplifiers, sensitive strain-gage signal conditioning often employed ac excitation and amplification coupled with either phase-sensitive demodulation or mechanical bridge-balancing techniques. For our applications in the LCP, ac signal conditioning still has inherent advantages.

The carrier amplifier/demodulator, in addition to the ac excitation power source, has three essential stages: an input amplifier stage, a demodulation stage, and a low-pass filter stage. In the demodulator stage, the ouput of the ac signal amplifier is, in effect, multiplied by the bridge excitation waveform. The dc or low-frequency noise is thus converted to signals near the carrier frequency; the desired signals near the carrier frequency, resulting from modulation of the carrier by gage resistance changes, are converted into dc or low-frequency signals. The low-pass filter stage then removes the high-frequency components of the demodulator output; the resultant dc output is proportional to the gage resistance change with no thermoelectric or low-frequency noise superimposed. The carrier amplifier/demodulator, however, is sensitive to noise near the carrier frequency and odd harmonics thereof. It can form "beat notes" with the odd harmonics. Addition of a bandpass filter before the input amplifier stage centered at the carrier frequency can attenuate the odd harmonics, but noise at the carrier frequency must be minimized by other means, such as selection of a carrier frequency outside of the noise spectrum. Transformer isolation, in addition to providing isolation from high voltage, also affords a means for isolating wide-band common-mode noise.

The Proposed System

General Description

The strain-gage signal-conditioning we have developed for the LCP is based on carrier-current excitation and phase-sensitive demodulation. Both isolated and nonisolated systems will be used, depending on the maximum substrate voltage to ground. The isolated system comprises double-shielded isolation transformers of our own design in both signal and excitation lines, narrow passband filters, and neutralizing adjustments for maximum rejection of electrical noise. The nonisolated system is similar to the isolated one, but it lacks the double shielding, bandpass filters, and neutralizing networks.

Detailed Description

Isolated system. The isolated system, shown in the block diagram (Fig. 1a) and the schematic diagram (Fig. 2), will be used with the gages mounted on the coil conductors. A 3-kHz excitation carrier at 5 v rms is coupled to the 0 to 90° balancing network via the special isolation tranaformer (Fig. 1b). The entire circuit on the secondary side of the transformer is enclosed in a floating shield, which is connected to the coil conductor through the internal cable shield at some point near the gage location. The object of this is to keep the gage, the circuitry, and the shields at the same potential. The isolation transformer (T_1, Fig. 2) has secondary taps to provide primary-to-secondary turns ratios of 1:1, 2:1, 5:1, and 10:1. This will allow us to select gage excitation levels between 0.5 and 5.0 V to provide a suitable compromise between gage excitation and gage heating. Resistors R11 and R20 provide a coarse balance for the two-arm strain-gage bridge connected to terminals A,B,C, of J3. The potentiometer R8 acts as a fine balance for the bridge. Both coarse and fine balance circuits are designed to minimize the current in the contacts of switch (S2) and the slider of R8. Resistors R2 and R3 are for series calibration of the bridge, while resistor R4

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balances the effect of resistor R2 during normal operation. Potentiometer R10 and capacitor C1 provide the means (mentioned earlier) for balancing the quadrature (capacitive) component of the bridge. Although some commercial carrier-amplifier-demodulator units come equipped with both in-phase and quadrature-balancing circuits, as well as calibrating provisions, it is to our advantage to include these in the circuit following the isolation transformer. If this were not done, both calibration and bridge balance would be upset when the gage excitation level is changed. Also, the coarse and fine balance controls provide a much wider range of adjustment than do those that generally are built into commercial carrier amplifiers. To help meet the space constraints inside the coil, the third (signal) wire of the strain-gage cable (Figs. 1a and 2) has been eliminated. Since the internal shield is already required, the system is designed so that the gage signal now appears as the ac difference between the internal shield and the adjustable center taps of the coarse and fine balance controls. Any imbalance in the completed bridge circuit appears between terminals 4 and 3 of the primary of the signal isolation transformer (T2). The secondary winding of T2 operates at ground potential. This shielding arrangement minimizes capacitive coupling to any external conductors, grounded or otherwise, i.e., electrical conductors that are not at the same potential as the substrate. In so doing, noise output (that which would result from the conversion of common-mode voltages to normal-mode voltages by any slight imbalances in the stray capacitance to external circuits) is minimized.

Even with the use of extensive shielding, a small amount of stray capacitance (at connectors, terminals, etc.) still exists between the enclosed circuit and objects at ground potential. Also, because this capacitance involves solid dielectrics with significant ac losses, the stray coupling that results is a combination of in-phase and quadrature components. The network comprising R11, R12, R13, C2, and C3 (Fig. 2) is for neutralizing this stray coupling. One of our primary concerns is to avoid the coupling of power-supply ripple voltages into the carrier amplifier input, especially those harmonics of 60 Hz that might "beat" with any of the odd harmonics of the carrier and produce a cyclic false output. This neutralizing network is very effective at the carrier frequency; however, because of its own phase shifts, it becomes ineffective at frequencies well removed from the carrier. For this reason, the bandpass filter, which has an attenuation of about 40 dB per octave, is inserted in the line between the output of T2 and the carrier amplifier.

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While the basic curcuit is designed to accept a two-armed strain-gage bridge, it can easily be modified to be used with a full bridge. When a quarter bridge is to be used, the additional bridge-completion network (shown in Fig. 1a) is required. The series resistor approximately balances the resistive component of the gage, while the capacitor roughly compensates for the capacitive imbalance caused by the leads between the completion resistor and the gage. This completion circuit is located as near as possible to the gage to minimize the capacitance that must be compensated before a true null voltage can be obtained. Fine adjustments of the quadrature balance are then made in the usual manner by the 90° balancing adjustment (R8).

<u>Nonisolated system</u>. The nonisolated system will be used with the gages mounted on the structural members. This is similar to the isolated system in regard to the carrier amplifiers and bridge-balancing circuits, but, because it operates with gages at ground potential, it does not use double-shielded isolation transformers, internal shielding, or bandpass filters. A 3-kHz transformer, used in the excitation circuit in place of T1 (Fig. 2), provides a selection of excitation levels for the gage and low-voltage isolation of the bridge from the grounded 3-kHz carrier output of the carrier amplifier module. A conventional third wire is used in the gage cable, and the quarter-bridge completion is identical to that of the isolated system, except for the internal shield arrangement.

Bench Tests

<u>Noise rejection (isolated system)</u>. Figure 3a is a block diagram of the test circuitry, in which the "noise" voltage was provided by a constant-amplitude variable-frequency oscillator. After all the bridge-balancing operations and the gain adjustments were made, the oscillator was set to a frequency near that of the 3-kHz carrier, and the neutralizing controls were adjusted for minimum beat note. The oscillator was than set to a 60-V (Peak-Peak) output level and manually swept from 20 Hz to 200 kHz as the output of the carrier amplifier demodulator was observed. Figure 3b is a plot showing the effect of the beat-frequency interference on the dc output of the carrier amplifier as a function of oscillator frequency. The peaks on either side of the carrier frequency occur because of the imperfect neutralization that occurs at frequencies other than the one at which the neutralizer was adjusted. The slight voltage at the 3-kHz carrier frequency (slot between the two peaks) is due to imperfect settings of the neutralizing adjustments. The measurement was taken when the low-pass output filter of the carrier amplifier was set for a 750-Hz bandwidth. These side-frequency peaks can be reduced by narrowing the bandwidth of the output filter to about 100-200 Hz. The diminishing peaks seen at 9, 15, and 21 kHz (and above) are due to the residual noise voltage that gets past the shielding, the neutralizer, and the bandpass filter, and beats with the third, fifth, seventh, and higher harmonics of the carrier at the phase-sensitive demodulator. Without the bandpass filter between the neutralizer and carrier amplifier, these peaks would be much worse. Overloading of the amplifier has been observed when the bandpass filter was removed.

Thermal drifts. Originally, our main source of instability resulted from the temperature coefficient of the passive bandpass filter, which we built from standard pot cores and capacitors. The effect was to shift the phase angle of the filter's output, thus degrading the output of the phase-sensitive demodulator. We have now overcome this problem by using a temperature-compensated, custom-made filter (Chesterfield Products, Inc., Saddlebrook, New York).

Long-term stability. The nature of the measurements and the low-level signals that will be available dictate that the system must have good long-term stability and that some means must be provided for periodically checking the zero reference and calibration. We simultaneously tested the stability of seven standard commercial carrier-amplifier-demodulator modules for a one-month period at maximum gain (× 10,000). The worst channel showed a maximum zero drift of 480 mV at the output (48 μV referred to the input), but the output of the best channel drifted only 20 mV (2 μV referred to the input). In operation, the zero reference of the carrier amplifier will be checked by shorting out the differential signal between the bandpass filter and the carrier amplifier.

Use Tests (Isolated System)

Figure 4a shows the installation of strain gages on one of the ISX toroidal field coils. Figure 4b shows typical traces of the measured strains as a function of time during the current pulses. These measurements were made with an early prototype, which, for administrative reasons, was located near the machine rather than in the data-collection area. The traces are therefore noisier (due to inadequate transformer shielding against magnetic fields) than they would have been if the system had been better shielded and/or located farther from the machine. This same early prototype was later used to measure strains at the finger joints of the ISX toroidal field coils. These measurements will be the subject of another presentation to be given at this symposium.[4] The isolation transformers have been redesigned and their shielding significantly improved since the first prototype was tested.

Conclusions

The two strain-gage signal-conditioning systems we have developed combine passive circuitry with commercial carrier amplifier modules to provide significant reduction of the effects of magnetic induction and thermoelastic potentials. In addition, the isolated version of the system allows strain gages to float at the electrical potential (up to 5 kV) of the substrate to which they are attached. It provides common-mode noise rejection of 120 to 140 dB for frequencies between 20 and 200 Hz and has means for making periodic zero-reference and calibration checks. Both versions of the system will be used in the LCP.

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2. G. J. Gabriel and J. A. Burkhart, "Potential Damage to DC Superconducting Magnets to High Frequency Electromagnetic Waves," Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, Tennessee (October 1977).
3. Howard C. Roberts, *Mechanical Measurements by Electrical Methods*, The Instruments Publishing Co., Inc., 1946, p. 138 (also, p. 320).
4. O'Toole et al., "Analysis and Test to Predict the Fatigue Life of the ISX-B Toroidal Field Coils' Finger Joints," Eight Symposium on Engineering Problems of Fusion Research, San Francisco (Nov. 13-16, 1979) to be presented.

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Fig. 1. Passive isolator with double-shielded transformers.

Fig. 2. Isolated system schematic design.

Fig. 3. Block diagram of bench test and its results.

Fig. 4. Strain measurements of ISX TF coil.

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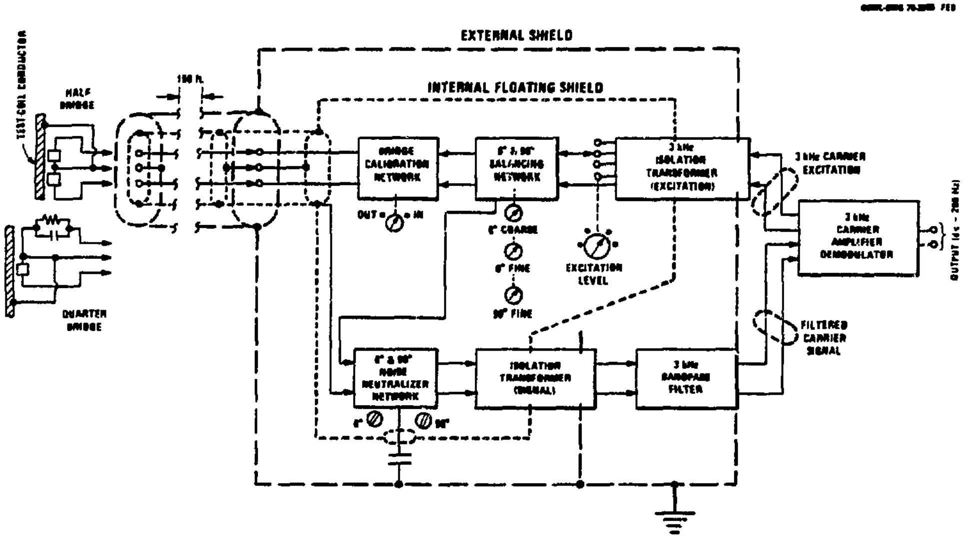

PASSIVE ISOLATOR

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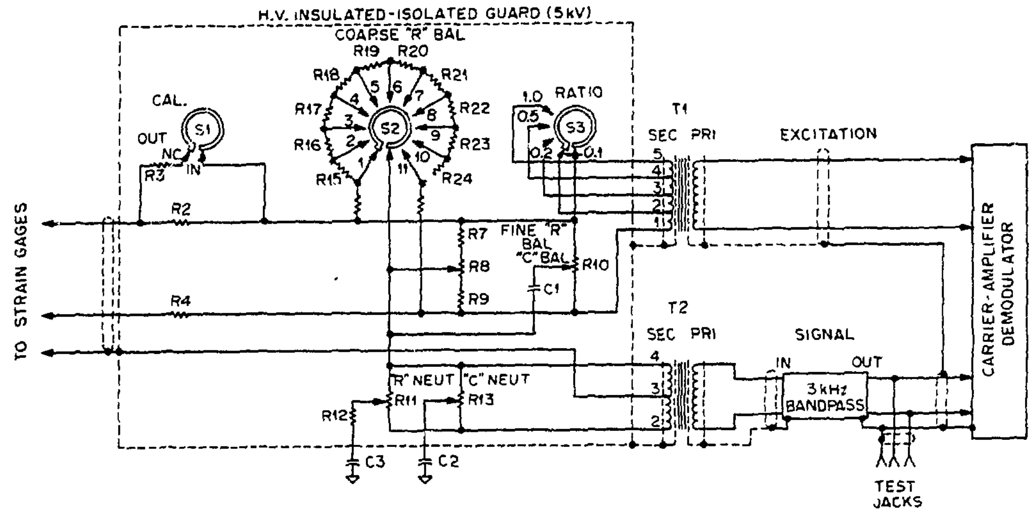

ISOLATED SYSTEM SCHEMATIC DIAGRAM

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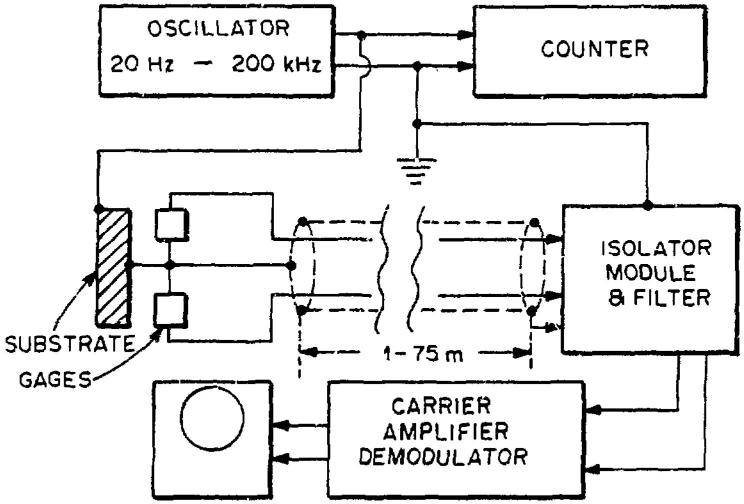
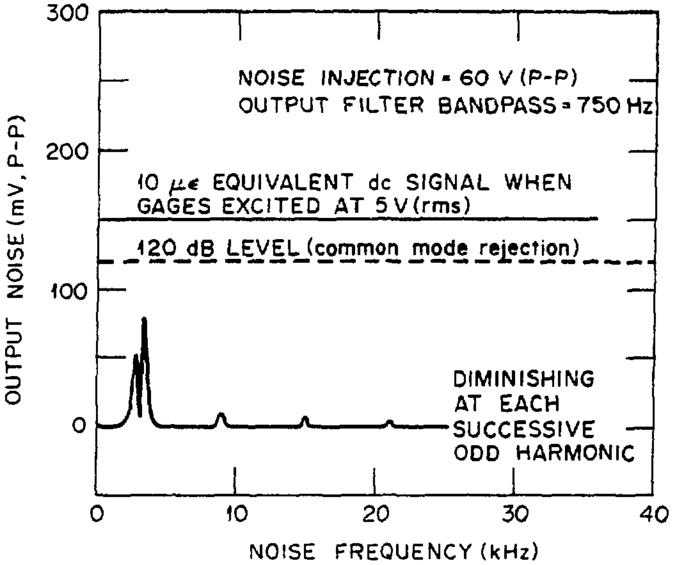


(*a*) BLOCK DIAGRAM OF BENCH TEST



(*b*) BEAT-FREQUENCY INTERFERENCE

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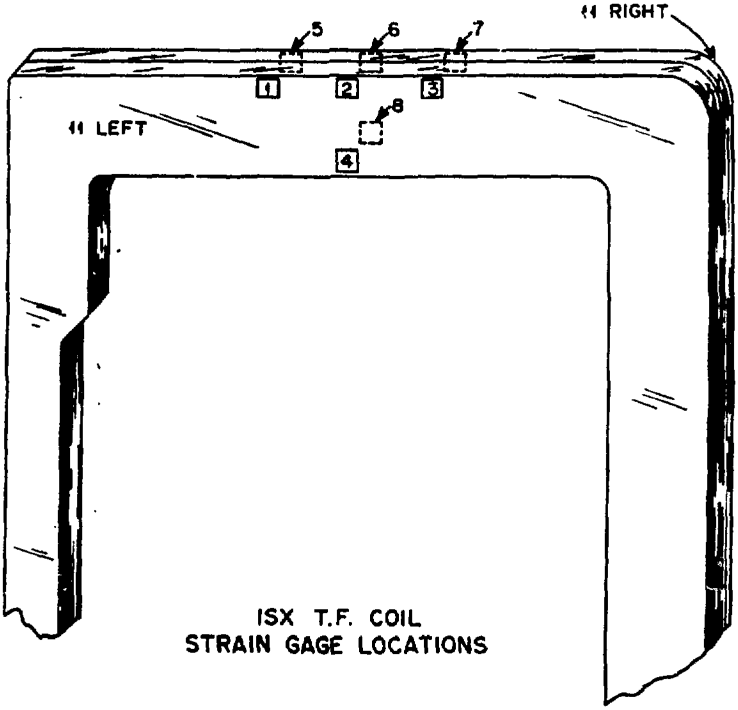

ISX T.F. COIL
STRAIN GAGE LOCATIONS

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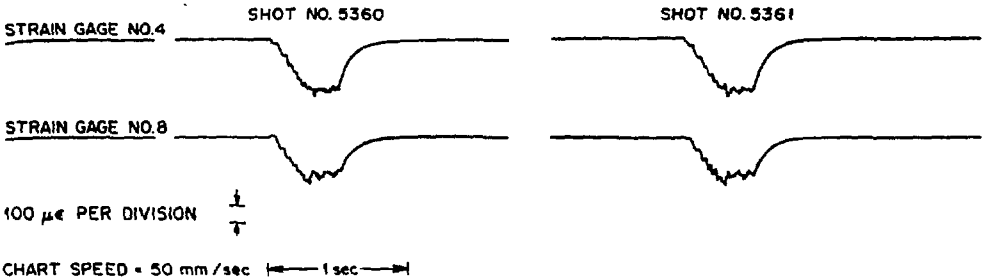

TYPICAL STRAINS OF ISX T.F. COILS 11L AND 11R
TAKEN WITH FIRST PROTOTYPE STRAIN-GAGE ISOLATOR