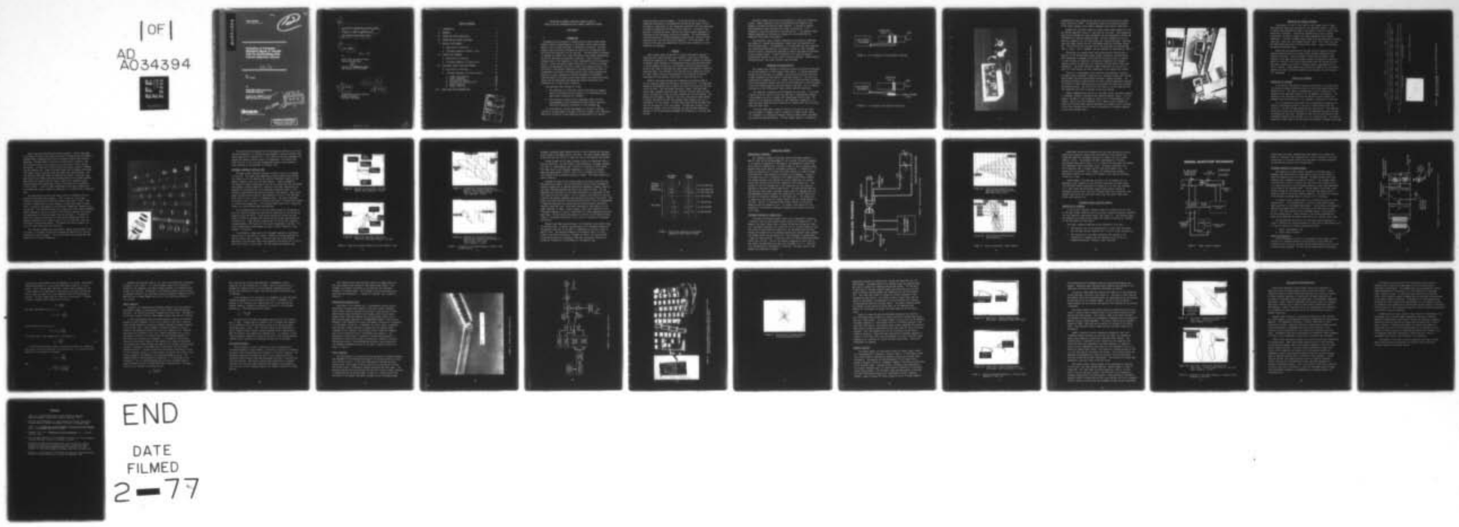
AD-A034 394 BATTELLE PACIFIC NORTHWEST LABS RICHLAND WASH F/G 20/3
EVALUATION OF COMPUTER SIMULATED SIGNALS OR METALLIC TABS FOR S--ETC(U)
DEC 76 J C CROWE N00024-75-C-4436

UNCLASSIFIED NL

1 OF 1
AD
A034394



END
DATE
FILMED
2-77

FC.

12

FINAL REPORT

Evaluation of Computer Simulated Signals or Metallic Tabs for Standardizing Eddy Current Inspection Systems

Dec 76

by
J. C. Crowe

To

Naval Ships Engineering Center
Hyattsville, Maryland

Contract No. N00024-75-C-4436 NEW
BNW Contract No. 2311102136

401 048

Battelle
Pacific Northwest Laboratories

6

EVALUATION OF COMPUTER SIMULATED SIGNALS OR METALLIC TABS FOR STANDARDIZING EDDY CURRENT INSPECTION SYSTEMS.

9

Final Report.

Dec 76

To

Naval Ships Engineering Center
Hyattsville, Maryland

15

Contract No. N00024-75-C-4436
BNW Contract No. 2311102136

By

11 Dec 76

10 J. C. Crowe

12 41p.

Nondestructive Testing Section
Battelle-Northwest
Richland, Washington

401048

1B

TABLE OF CONTENTS

EVALUATION OF COMPUTER SIMULATED SIGNALS SYSTEM OR METALLIC TAB FOR STANDARDIZING EDDY CURRENT INSPECTION SYSTEMS

Final Report

INTRODUCTION

Nondestructive evaluation of tubing using the eddy current method normally requires standardization or calibration of the testing system against a set of known conditions or references (standards). The most commonly used calibration references are sections of tubing containing fabricated flaws machined into the tube wall. The eddy current instrument is adjusted to produce one or more calibrated signal outputs representing the various desirable or undesirable conditions. This calibration procedure aids in the immediate or later interpretations of the inspection results. Within the current state of practice, it is difficult to make accurate and reproducible artificial flaws in the reference tubing. The variations in the physical dimensions of the fabricated flaws result in corresponding variations in the test results. This report presents the results of a study undertaken at Battelle-Northwest to investigate alternate means of calibration which might reduce the uncertainties experienced with the fabricated flaw method and improve the accuracy and reproducibility of eddy current inspection.

Two approaches were selected for study:

1. The production of calibrating signals from specially prepared metallic-calibration tabs or passive coils translated past the eddy current inspection coil assembly.
2. The injection of electronically developed signals into the electromagnetic field surrounding the eddy current inspection probe which represent calibration or flaw responses.

Our investigations included development of the metallic tab and electronics systems needed to produce calibration signals, and a laboratory feasibility evaluation of each technique for application to a specific tubing and eddy current instrument. A brief description of the basic inspection technique and instrumentation used during the study is given, followed by a description of the "comparison specimens" that were fabricated to generate conventional calibration signal patterns. The metallic tab approach, including tab types, designs, and signal patterns generated, is discussed and the laboratory results are presented. The electromagnetic injection technique, including breadboard system design, injection signal characteristics, and resulting signal patterns, is also described. The results of the study are examined and the merits and limitations of each technique are discussed.

APPROACH

Eddy current system calibration is usually performed by passing a reference tube containing known flaws (naturally occurring or machined) through the inspection coil assembly. The instrument response is adjusted to produce signal patterns of a predetermined size, shape and phase angle. To assure adequate calibration, the reference tube must produce signals covering the range of amplitudes and phase angles encountered for naturally occurring flaws. Our approach in this program was to compare the variety of signal patterns that can be generated by the alternate calibration techniques with the patterns from natural or machined tube flaws.

Metallic tab signal patterns were produced by translating tabs of various types and geometries through an OD inspection coil. The tabs were mounted on nonconductive rods to permit convenient positioning of the tabs within the tube. Tabs fabricated from brass, copper, stainless steel, carbon steel, magnetic recording tape, ferrite, and other materials were used to evaluate the variety of signal patterns that can be produced. The effects of tab geometry, material, size, size, and position were studied to permit fabrication of tabs that produce signal patterns similar to calibration or flaw signals. ID tabs (tabs placed inside the tube) were used for the majority of our tab studies. OD tabs were included in our evaluation, however, they are impractical for most OD tube inspections because of the limited clearance between the inspection coil and the tube surface.

Passively loaded coils were also evaluated as a source of calibration signals. Bobbin loadingcoils were translated past the inspection coil assembly to produce calibration signal patterns. A variety of patterns were produced by connecting electrical loads, consisting of R-L-C components, across the terminals of the passive coils. The range of signal patterns generated by the passively loaded coils was established for comparison with actual flaw patterns.

The electronic signal injection technique was evaluated by observing the effects of injected electromagnetic signals upon the inspection coil and instrument output. Electromagnetic coils positioned near the inspection coil were excited electronically to produce a variety of signal patterns. Digital circuitry concepts were developed to control the phase and amplitude of the injected signals. ID and OD injection coils were evaluated to determine the flexibility of the signal injection technique. Signal patterns simulating actual flaw signal patterns were developed.

INSPECTION SYSTEM DESCRIPTION

Our research was directed to developing alternate calibration techniques for the OD inspection of 70-30 copper nickel tubing. In the OD inspections (Figure 1A) an induction coil assembly, consisting of two encircling coils, is held stationary and the tubing is translated through it. The coils are differentially connected to an a.c. bridge circuit within the test instrument to aid discrimination against variations in tube dimensions or other characteristics that change gradually along the length of the tube. This is commonly referred to as the "differential" eddy current inspection technique.

The "absolute" inspection coil arrangement was also used. In this mode (Figure 1B) one of the coils encircling the tube is disabled and replaced in the bridge circuit by a balance coil located away from the tube. The "absolute" coil responds to changes in tube dimensions, conductivity, or other variation along the tube in addition to irregularities such as cracks, holes and other flaws.

The Nortec Model NDT-6, shown in Figure 2, was used for our tests. This instrument is commonly used for inspection of copper-nickel tubing. The instrument is a selectable frequency high gain eddy current instrument with phase and amplitude outputs. The two channel output is a quadrature

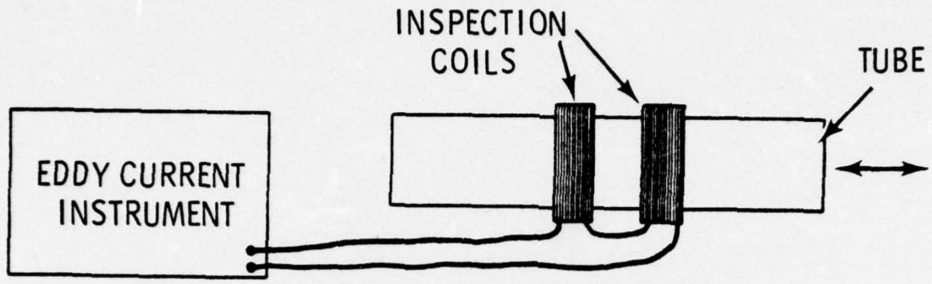


FIGURE 1A. O.D. Differential Tube Inspection Technique

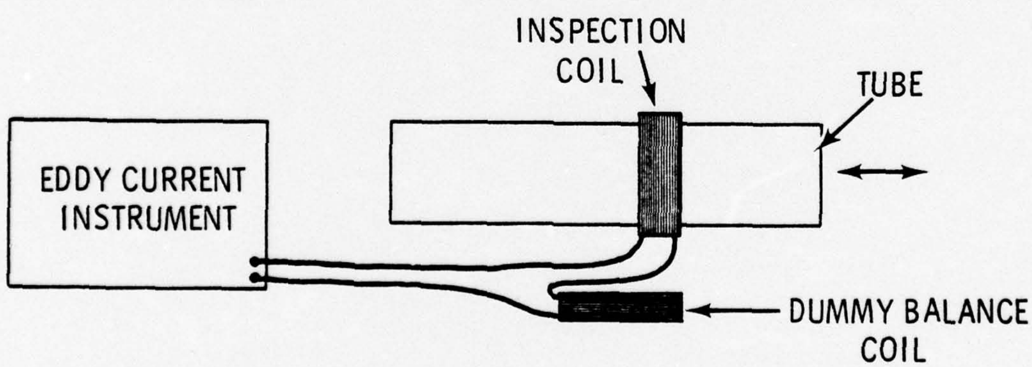


FIGURE 1B. O.D. Absolute Tube Inspection Technique

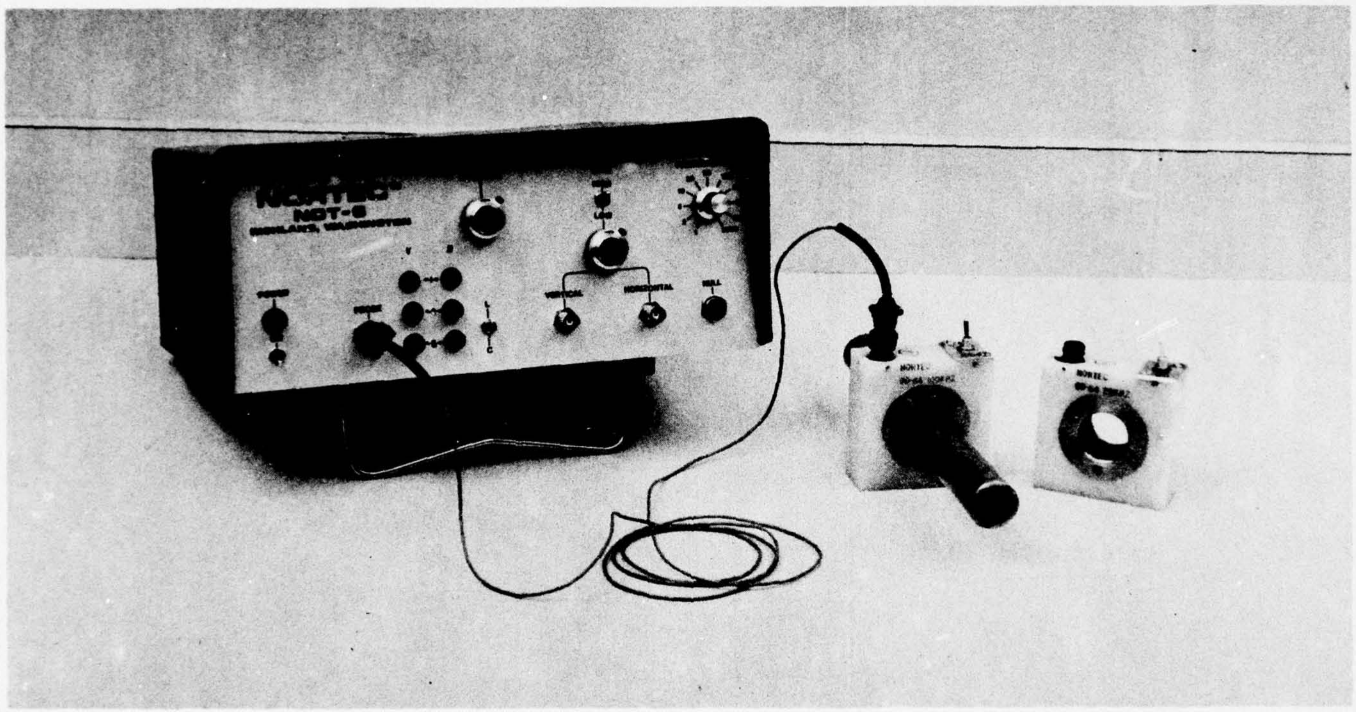


FIGURE 2. Eddy Current Instrument and Probes

presentation of the voltage across the test coil with provision for phase angle rotation of 0-360^{o}. The quadrature outputs allow detailed analysis of the signal response using complex impedance plane analysis techniques.

Commercially available inspection probes, Nortec Models OD-64 for 5, 20 and 100 kHz operation (Figure 2), were used for the tests. These probes are specifically designed for tubing inspection and are switchable to either the differential or absolute inspection mode. The dual inspection coils are wound on a phenolic coil form and fitted into a nylon probe body. Stainless steel end plates protect the coil from damage caused by misaligned tubing, etc. The encircling coils mounted within the probe body are approximately .050 in. wide, 1 1/8 in. diameter, and are separated by approximately .025 in.

Discussions with copper-nickel tubing manufacturers revealed that a majority of the in-plant eddy current tubing inspections are performed at test frequencies of between 5 and 20 kHz for the tubing size of interest. In order to make our laboratory investigation compatible with standard industry practice a majority of our laboratory work was done at these test frequencies. The result obtained at these frequencies can serve as the basis for investigations at other frequencies or more generalized studies.

Figure 3 is a photograph of the laboratory test apparatus including the eddy current instrument, inspection coil, transport system, oscilloscope, tubing sample and other miscellaneous electronic support equipment. The laboratory transport system consists of a small variable-speed motor designed to rotate four rubber covered rollers which contact the tube above and below the outside surface. The rollers drive the tube at a uniform speed through the inspection coil which is mounted to the drive housing.

Complex impedance plane analysis of the eddy current instrument response is extremely valuable in evaluating and comparing complex signals. For this reason a storage X-Y oscilloscope was used to aid in interpretation of the results. Much of the data presented in this report are oscillographs of actual oscilloscope signal patterns generated by the eddy current instrument. A strip chart recorder was also used for recording the instrument response to real and simulated flaws.

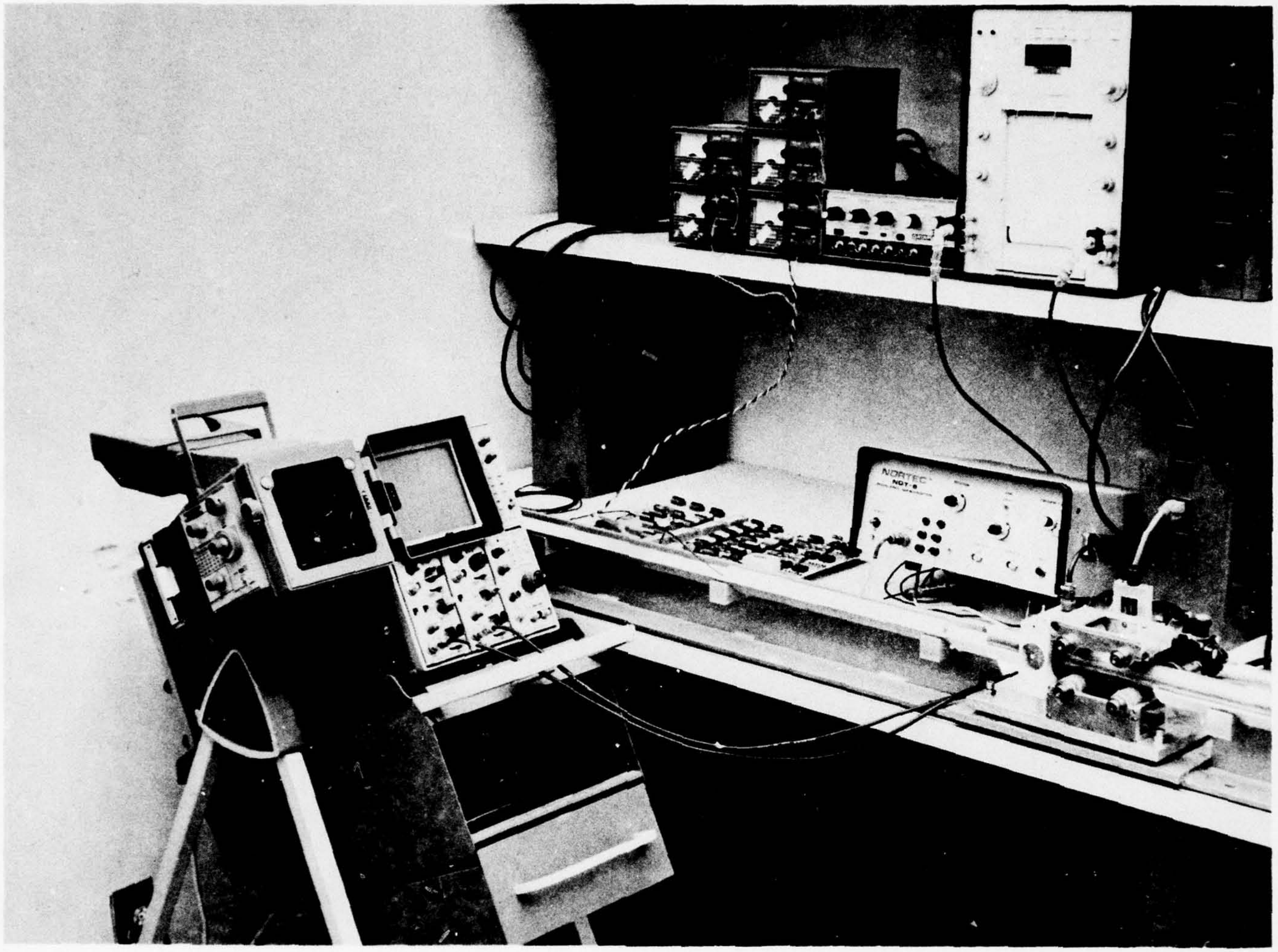


FIGURE 3. Laboratory Test Apparatus

COMPARISON AND CONTROL SPECIMENS

Tube samples of 1.05 in. OD, 0.065 in. wall copper-nickel (70-30) heat exchanger tubing were obtained for our laboratory studies. A series of defects were machined into some of the samples to serve as typical tube calibration references. The machined references were used to compare conventional calibration signals with those produced by the alternate techniques. A variety of defects were placed in the machined tubes including outer wall, inner wall, and through the wall flaws. Drill holes, saw cuts, and EDM notches were used to simulate actual flaws. Figure 4 illustrates the machined reference tubes.

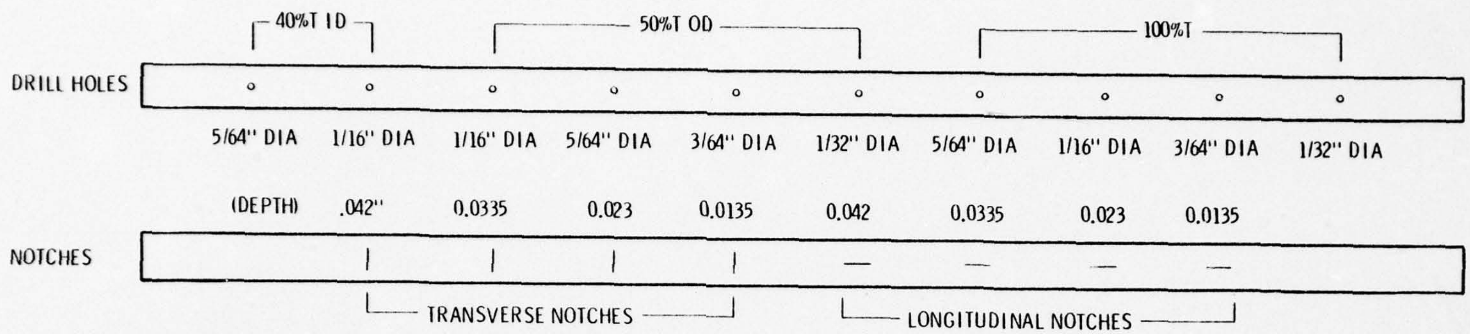
These tubes were examined with the eddy current inspection system to establish baseline data and to obtain signal patterns generated by the machined flaw types. The oscillograph at the bottom of Figure 4 shows examples of the eddy current instrument response (differential inspection mode) to a series of drill holes (approximately half-way through the wall). The signal patterns are typical of patterns normally generated for drill holes in tubing. These patterns were utilized to establish the relationship between the normal calibration techniques and the metal tab and injection coil techniques.

METALLIC TAB APPROACH

DESCRIPTION OF TECHNIQUE

In the metallic tab approach selected tab materials are placed inside the tubing to produce calibration signals as the tubing passes through the inspection coil. The signals are generated by the coil response to the presence of the additional conductive or ferromagnetic tab material. The response of the inspection coils and the resulting signal patterns are dependent upon the tab material, size, geometry, orientation and position.

In our laboratory work the metal tabs are permanently mounted on non-metallic, non-conductive tubes or rods just slightly smaller than the tubing ID. The rods are then placed inside a tube section. This technique proved quite useful and satisfactory for the laboratory evaluation and may be adequate for field use. Non-metallic rods also allow evaluation of the instrument response to the tab when it is not inside the tube. This permits comparison of tab signals with and without the presence of copper-nickel tube.



FLAWS SPACED AT ~ 3" INTERVALS ALONG TUBE

FIGURE 4. Machined Flaw Specimens and Typical Instrument Response to 50% T O.D. Drill Holes

Some of the tabs evaluated are shown in Figure 5. Efforts were made to use materials over a wide range of electrical conductivities and magnetic permeabilities to determine the limits or range of signals that could be generated. The tabs shown in the photo include several cylindrical tabs. The tab design shown in the close-up view at the top of Figure 5 proved most useful. It consists of a short metal ring slightly larger in diameter than the mounting rod. Rings of various lengths and thicknesses fabricated from copper, brass, stainless steel and carbon steel were evaluated. The ring tabs are relatively simple to fabricate and adjust. Note that rings were metal strips formed around the nonconductive rod and soldered together. Good electrical contact along the seam is required for greatest signal response because the induced eddy currents flow around the circumference of the cylinder. A split cylinder (unsoldered at the seam) produces only an insignificant signal response in comparison to a cylinder with a conducting seam.

The phase angle at which a tab signal occurs is affected by the tab material and the operating frequency. This is true for a tab placed inside the inspection coil without the copper-nickel tube in place. When the tab is placed inside the tube, however, an additional amount of phase shift is caused by the presence of the tube wall between the inspection coil and the tab. This additional phase shift rotates the normal complex impedance plane presentation (as will be shown in the following section) and affects the phase region in which the signal from the tab occurs. The amount of phase shift varies with the type of tubing being inspected and thus, the patterns presented in this report are valid only for the type, size, and thickness of tubing being studies. The general principles, however, are valid for other tubing and test situations.

The tube wall presence also significantly reduces the amplitude of the tab signal. The amount of phase shift through the tube wall will also be related to the test frequency. This must be taken into consideration when operating at other test frequencies.

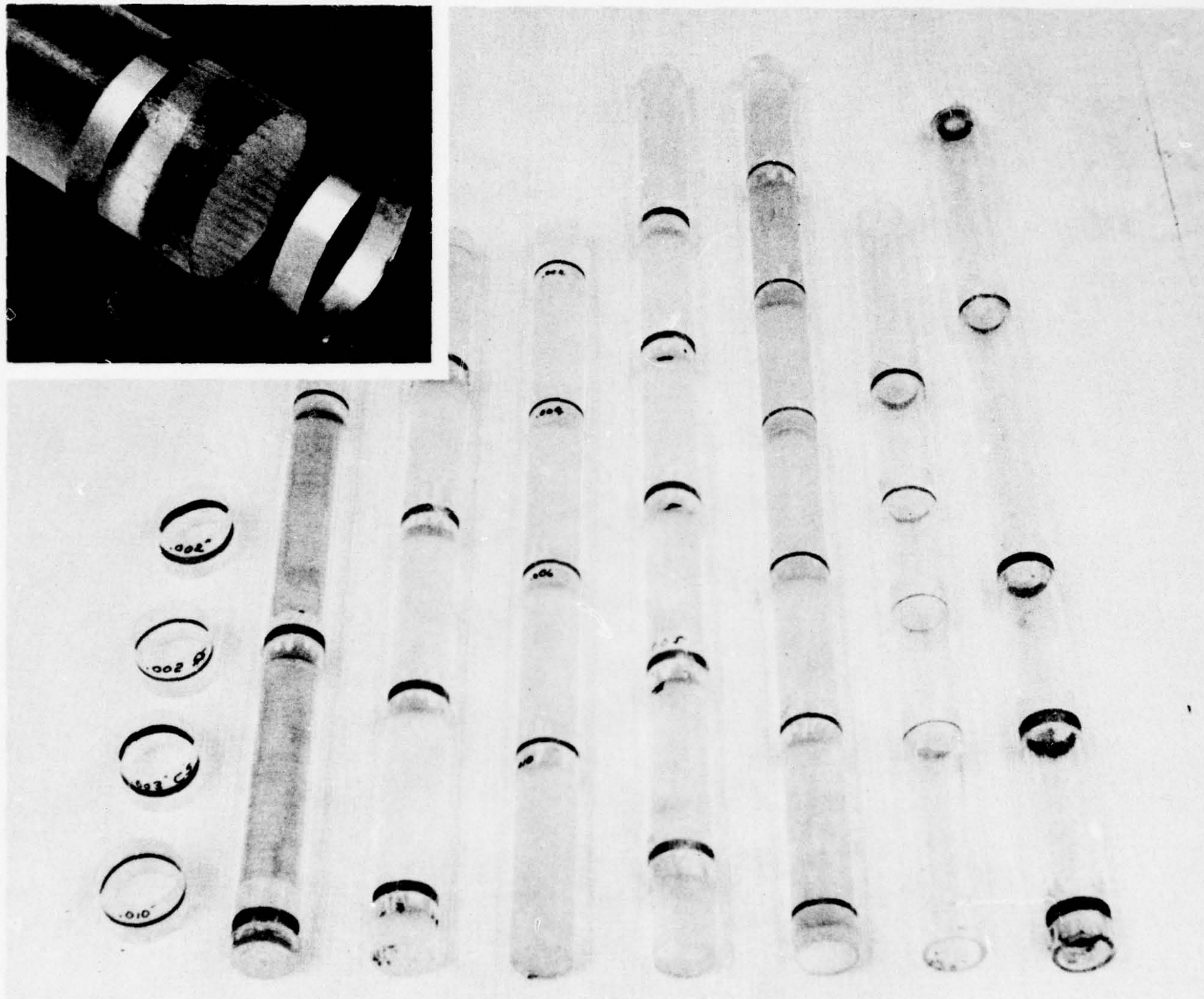


FIGURE 5. Various Metallic Tabs with Enlarged View of Cylindrical Tab (insert)

The calibration tab approach has the advantage of simplicity, but lacks flexibility because it is limited to the placement of tabs on surface of the tubing opposite the inspection coil. This restricts the tab arrangement and reduces the number of patterns that can be generated. Our studies have shown that this is not a serious disadvantage because a wide variety of signal patterns can be obtained with internal tabs.

INSTRUMENT RESPONSE TO METALLIC TABS

The eddy current instrument response to metallic tabs is illustrated in Figure 6A. The signals were generated by passing several tabs through the inspection coil and observing the absolute instrument response on the complex impedance plane (no Cu-Ni tube present). These tab materials illustrate the range of phase angles that can be covered with tabs fabricated from commonly available materials. Materials with other conductivity and permeability characteristics can be selected to generate signals in the clockwise region between the ferrite and copper ring response. Eddy current theory indicates that no metallic tab response will occur in the left hand plane (left of null) of the X, R impedance plane. The signals generated by the brass rings in Figure 6A illustrate the effect of varying the thickness of cylindrically shaped tabs. This provides added flexibility in producing signals at a desired phase angle and amplitude.

The increased phase shift of the tab signals caused by the presence of the Cu-Ni tube wall between the tabs and the inspection coil can be seen by comparing Figure 6B and 6A. Figure 6B was obtained by placing the tabs within a section of unflawed Cu-Ni tubing and passing the tube through the inspection coil. Note that the primary effect of the tube wall presence is approximately a 90^{o} rotation of the patterns generated by the tabs. The relative phase angle spread between the tabs is nearly identical to the patterns in Figure 6A.

The differential mode (dual coil) instrument response to cylindrical metallic tabs is the familiar "figure 8" pattern of the type generated by many artificial flaws in tubing. Figure 7A shows the signal patterns generated by the stainless steel rings compared to the pattern for a 1/16 in. 100% T drill hole in a Cu-Ni tube. The tab length and thickness were

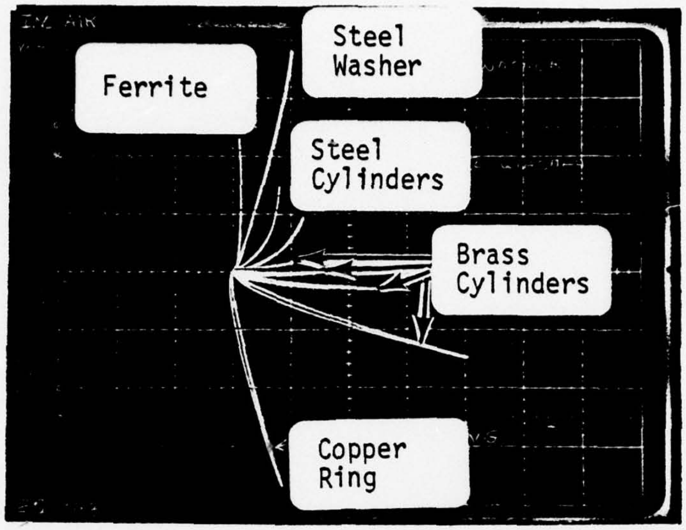


FIGURE 6A. Response to Various Tabs - No Tube Present (test frequency = 20 kHz)

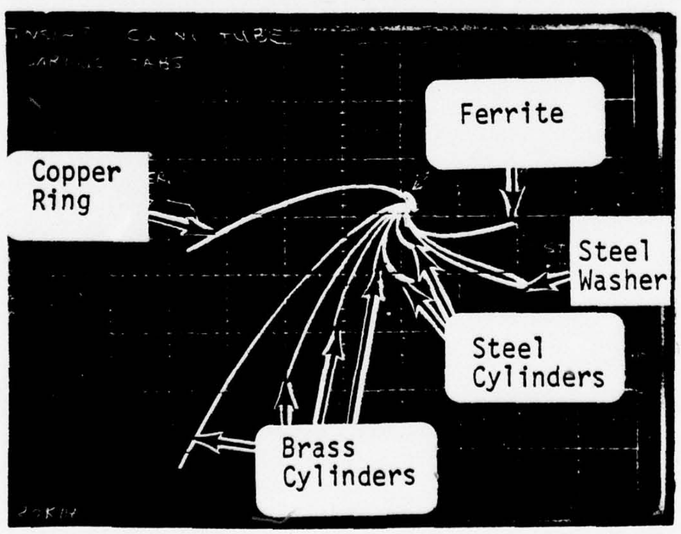


FIGURE 6B. Response to Same Tabs as 6A Placed Inside CuNi Tube (test frequency - 20 kHz)

FIGURE 6. Absolute Instrument Response to Various Metallic Tabs

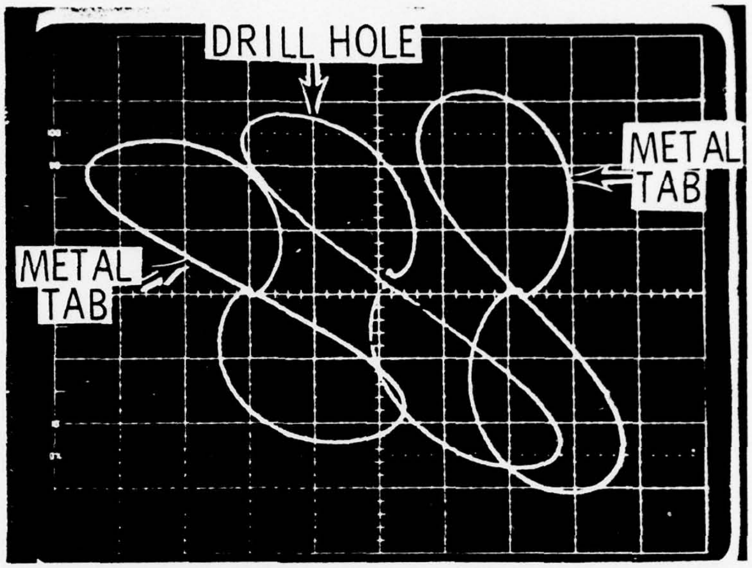


FIGURE 7A. Differential Instrument Response to Metallic Tabs (outer traces) and 1/16 in., 100%T Drill Hole (center trace) (test frequency = 20 kHz)

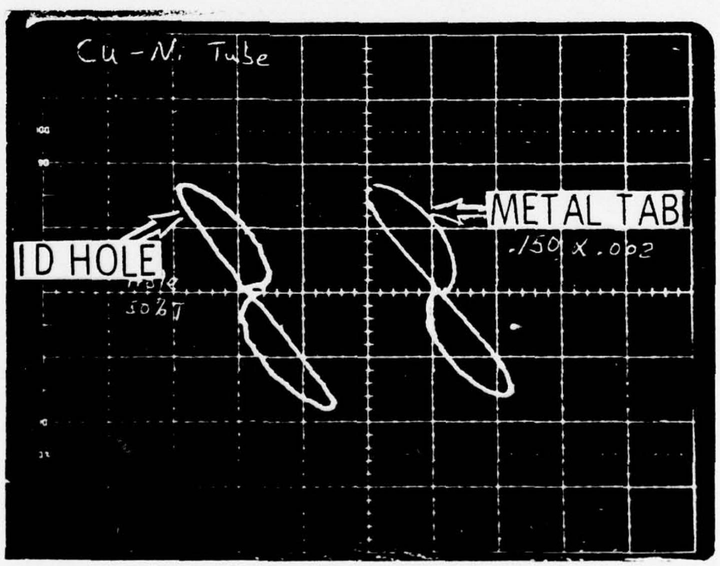


FIGURE 7B. Differential Instrument Response to Metallic Tabs (right trace) and 5/64 in., 40%T ID Hole (left trace) (test frequency = 5 kHz)

FIGURE 7. Differential Instrument Respone to Metallic Tabs and Drill Holes

selected to produce signal patterns similar to the flaw when the tabs were placed inside an unflawed region of the tube. The signal pattern generated by the tabs are very similar in shape and size to the machined flaw pattern.

Another example of tab signal patterns similar to fabricated flaws is shown in Figure 7B. The left trace is the differential instrument response to a 5/64 in. (approximately 35% T) ID hole in a section of Cu-Ni tubing. The right trace is the instrument response to a cylindrical stainless steel tab approximately 0.150 in. wide, 0.75 in. diameter and 0.002 in. thick placed inside an unflawed section of tubing. The signal patterns are nearly identical.

Although the metallic tab signals shown do not exactly duplicate the fabricated flaw signals, they are sufficiently similar to be considered as possible alternatives to machined calibration references, however, there is one major difference between the signals that should be noted. The tab generated signal patterns are many times generated at a phase angle of 180° with respect to the flaw signal. This is caused by the location of the tab signal on the complex impedance plane relative to an actual flaw signal. This causes the signal patterns from the tabs and artificial flaws to be generated in opposite directions even though the oscilloscope patterns have nearly identical shape and size. Strip chart recordings of the signals will not appear identical in shape. Figure 8 shows a strip chart recording of the instrument response to a series of machined drill holes compared to stainless steel tabs. The tab signals are opposite in polarity to the machined flaws. Figure 8 illustrates the potential use of tabs for recorder and instrument calibration.

Magnetic tape tabs were evaluated in the laboratory using several types of recording tape. In general the amplitude of the instrument response to the magnetic tape tabs is very small in comparison to artificial flaws or metallic tabs. The absolute response to the magnetic tabs is a slight offset in the ferrite direction. Attempts to control the signal pattern by recording signals on the magnetic tape were unsuccessful because the system was insensitive to the presence of the magnetic tape.

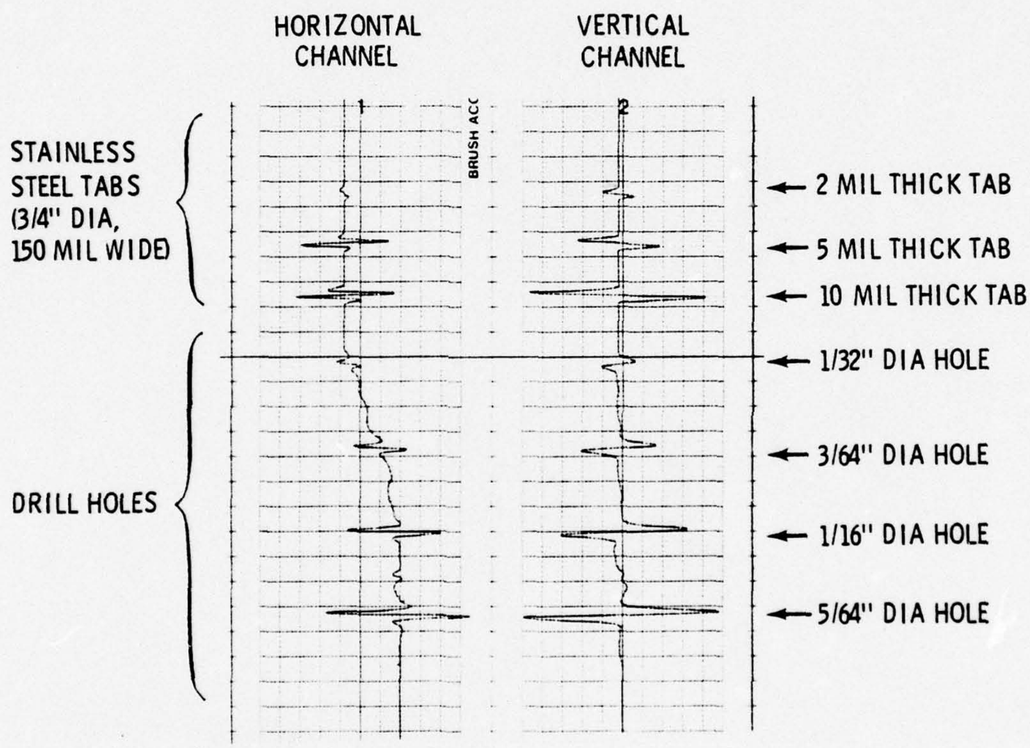


FIGURE 8. Strip Chart Recording of Instrument Response to Tabs and Drill Holes

LOADING COIL APPROACH

DESCRIPTION OF TECHNIQUE

Our laboratory studies of the eddy current instrument response to metallic tabs led to the development of still another calibration approach. It is actually an extension of the metallic tab concept and involves the use of passive "loading coils" in place of metallic tabs to produce signal patterns that can be used for instrument calibration. A "loading coil" is simply an induction coil (similar to an eddy current coil) that has added fixed electrical load consisting of passive R-L-C components. Figure 9 illustrates the use of a loading coil for producing calibration signals. The voltage induced in the loading coil by the inspection coil causes a current flow through the electrical impedance of the loading coil. This electrical load is reflected back to the inspection coil and causes an imbalance in the eddy current bridge circuit. The amplitude and phase of the resulting eddy current instrument output signal is dependent upon the electromagnetic coupling between the inspection coil and the loading coil, and upon the electrical impedance of the loading coil. The loading coil is wound on an insulating rod slightly smaller than the inside diameter of the tube. The coil is then positioned inside a section of tubing and passes through the inspection coil. The leads of the loading coil are connected to an externally selectable impedance which serves as the electrical load.

INSTRUMENT RESPONSE TO LOADING COILS

A variety of instrument output signals can be generated by selecting a different load for each successive pass through the inspection coil. For example, the signal traces shown in Figure 10A are the differential (dual coil) instrument responses to a loading coil with a variable resistive load. The resistive load across the loading coil was increased after each pass through the inspection coil to generate successively smaller signal patterns. The largest pattern was generated with a load resistance of approximately 3 ohms (far right pattern). A resistive load of 50 ohms produced the pattern second from the left. The far left pattern, appearing as just a dot on the screen, was generated by an open coil (unloaded or $R = \infty$). Note that only the amplitude of the patterns is affected. The phase angles of the pattern are essentially constant.

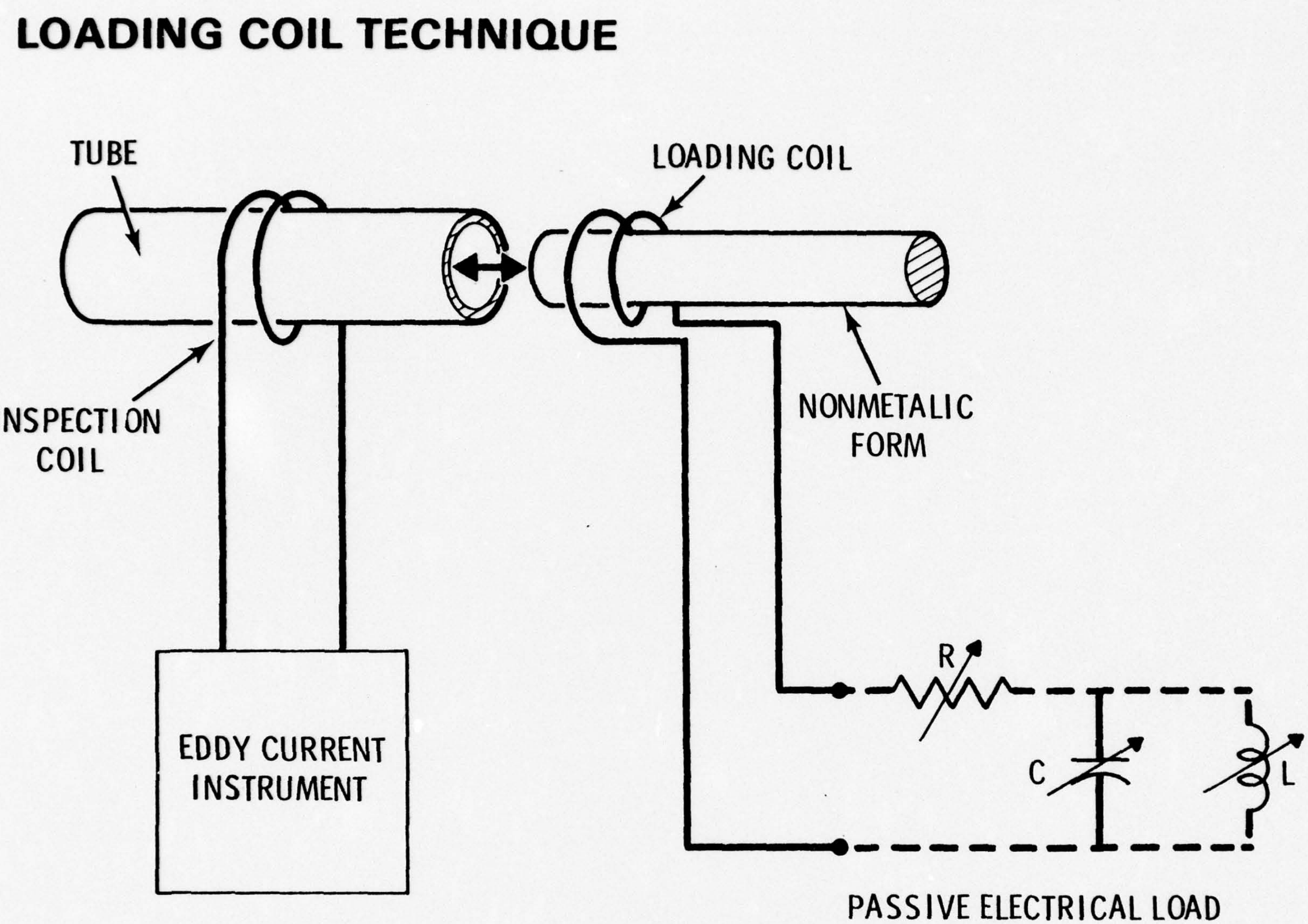


FIGURE 9. Passive Loading Coil Technique

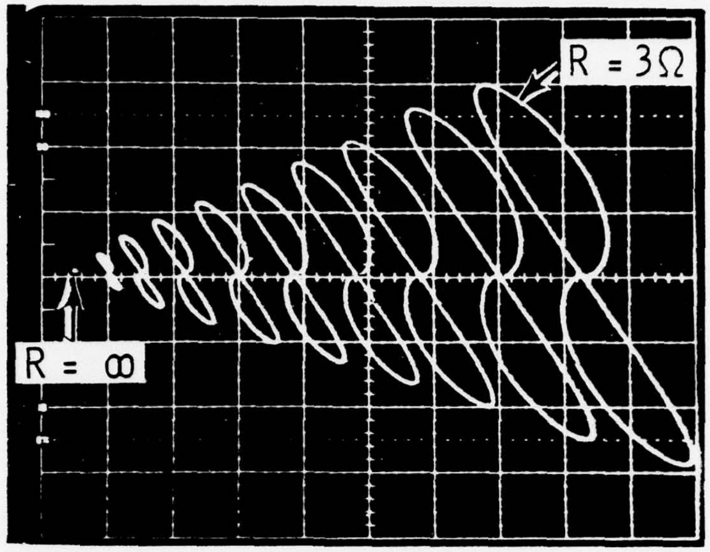


FIGURE 10A. Signal Pattern Generation and Amplitude Control Using Variable Resistance Loading Coils

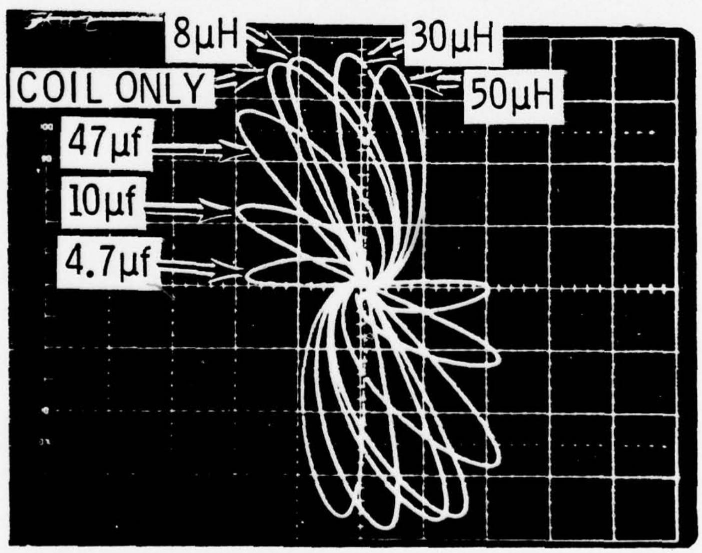


Figure 10B. Signal Patterns Generated Using RLC Loading Coils

FIGURE 10. Passive Loading Coil Signal Patterns

Phase angle shifts are introduced into the signal patterns by placing inductive or capacitive loads across the terminals of the loading coil. Figure 10B shows the instrument response to a loading coil with various loads of L and C. The patterns are shown superimposed to illustrate the possible phase angle shifts. A 4.7 μF capacitive load across the loading coil generated a nearly horizontal trace. The pattern generated with a 50 μH inductive load is rotated over 90^{o} from the horizontal axis. The shorted coil (no external R or C added) lies between these extremes. Amplitude variations are caused by differences in the internal resistance of the L or C load.

These patterns illustrate the flexibility of the loading coil for generating signal patterns at many different amplitudes and phase angles. The $>90^{o}$ phase rotation obtained with loading coils at this test frequency (f = 5 kHz) covers the approximate range of phase angles produced by machined ID and OD flaws. Note that although higher test frequencies cause greater phase shifts for subsurface flaws, they also cause larger phase shifts with loading coils.

ELECTRONIC SIGNAL INJECTION APPROACH

DESCRIPTION OF TECHNIQUE

In the "signal injection" approach signals are injected into the field of the eddy current inspection coil by exciting a separate induction (injection) coil with specially constructed signals (see Figure 11). The injected signals are detected by the eddy current inspection system and displayed or recorded in the same manner as flaw signals.

The signal injection technique can be implemented in two ways:

1. The injection coil can be impressed with a fixed signal and moved past the eddy current inspection coil ("static" signal injection) or,

2. The injection coil can remain stationary with respect to the inspection coil assembly and the impressed signal varied in a predetermined manner ("dynamic" signal injection).

SIGNAL INJECTION TECHNIQUE

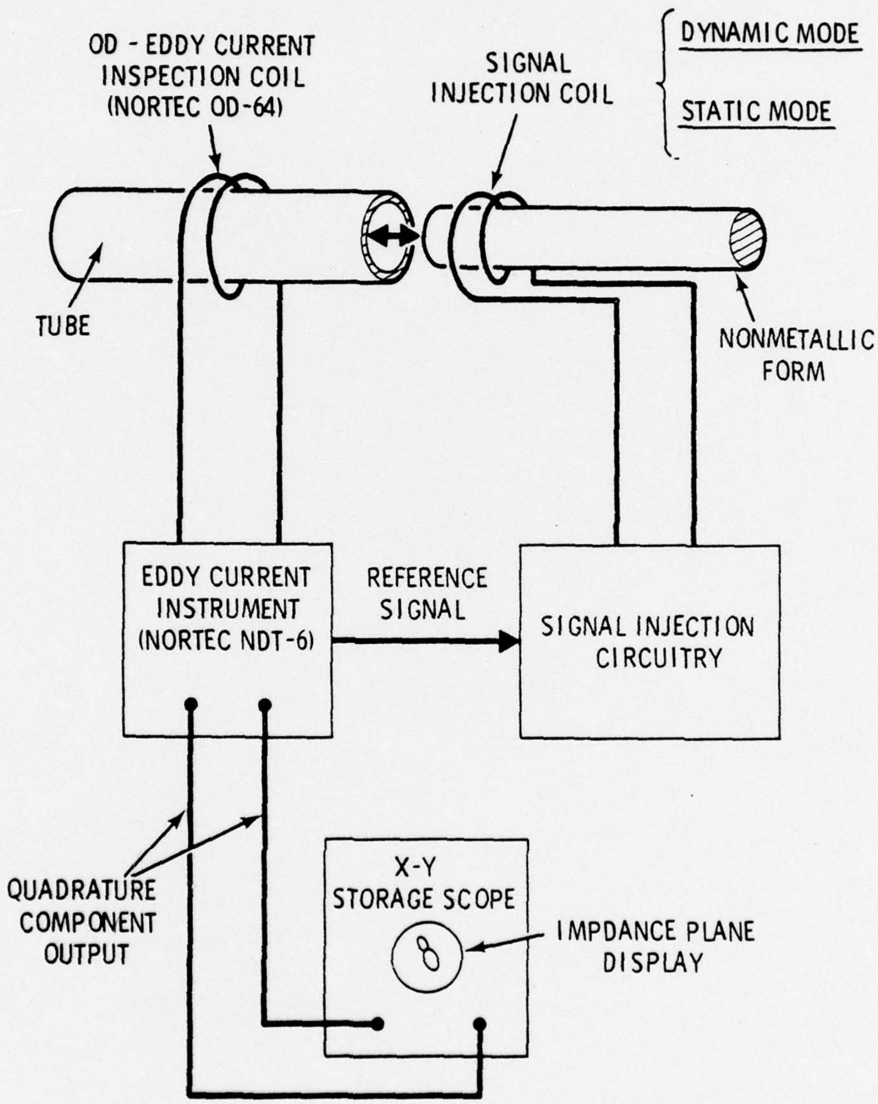


FIGURE 11. Signal Injection Concept

In both cases the signal impressed upon the injection coil upsets the normal null balance of the inspection coil circuit, resulting in a signal at the output of the eddy current instrument that is directly related to the amplitude and phase of the injected signal.

INSTRUMENT RESPONSE TO INJECTED SIGNALS

The response of an eddy current instrument to injected signals is dependent upon the particular bridge balance circuit and the manner in which the inspection coils are connected. The NDT-6 bridge circuit and inspection coil connection are shown in Figure 12. The injected signal resulting from a "static" injection coil moving past the inspection coil is a single excursion of the instrument output at a phase angle determined by the phase of the injected signal. The amplitude of the bridge circuit output increases as the injection coil draws near the inspection coil, readhing a peak at the point of maximum coupling. The normal null balance of the bridge is restored when the injection coil is withdrawn.

In "dynamic" signal injection the coil is stationary relative to the inspection coil. The injected signal is varied in amplitude and phase angle according to a pre-established pattern. This produces a corresponding amplitude and phase excursion at the output of the eddy current bridge circuit. The signal pattern at the instrument output is thus controlled by the injected signal. Signal patterns of any desired amplitude and shape can be generated by properly manipulating the injected signal input.

The undirectional excursion of the instrument output produced by a "static" injection coil can be explained by an analysis of the bridge circuit in Figure 12 under two different operating conditions:

1. Normal flaw detection, and
2. Static signal injection.

Normal Flaw Detection

In the discussions to follow it is assumed that the bridge circuit is initially in a balanced condition with the tube in place within the inspection coils Z_1 and Z_2, and that the two potentiometer slide wires are at their center positions. It will also be assumed that the resistances

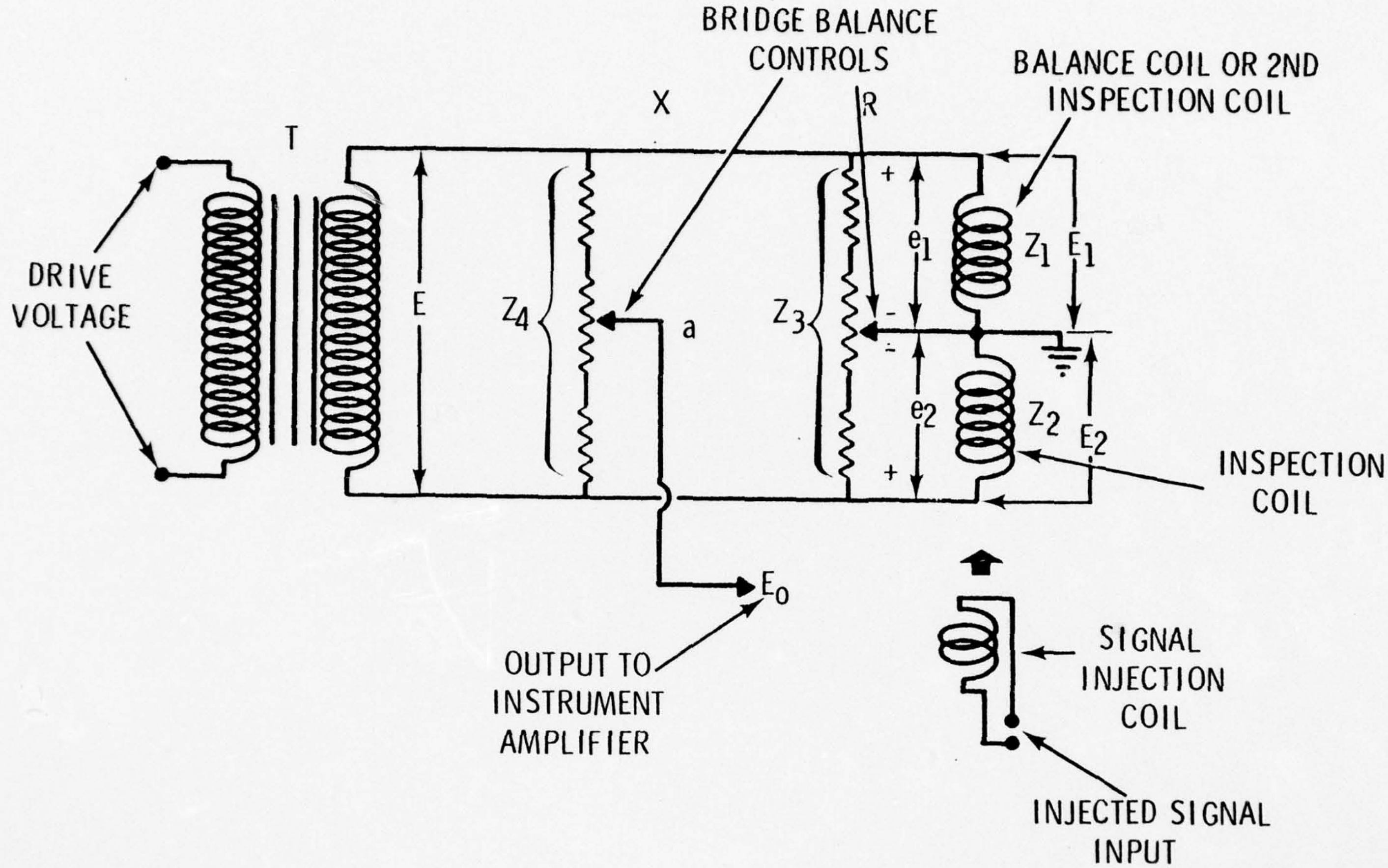


FIGURE 12. Eddy Current Inspection Coil AC Bridge Circuit

Z_3 and Z_4 are large compared with the impedance of Z_1 and Z_2. Under these idealized conditions $Z_1 = Z_2$ and the bridge output signal E_o is a null signal. It will now be shown that when a tubing flaw is adjacent to coil Z_1 the bridge will be imbalanced in one polarity direction, and when the flaw is under the other coil Z_2 the imbalance signal will have opposite polarity. We shall assume that the bridge drive transformer 'T' produces an output voltage E which produces a coil current.

$$I_c = \frac{E}{Z_1+Z_2} \tag{1}$$

The signal developed across coil Z_1 is

$$E_1 = I_c Z_1 = \frac{EZ_1}{Z_1+Z_2}$$

and the signal across Coil Z_2 is:

$$E_2 = I_c Z_2 = \frac{EZ_2}{Z_1+Z_2} \tag{2}$$

The bridge output signal between point a and ground is:

$$E_o = \frac{E_1+E_2}{2} \tag{3}$$

Since the bridge output voltage is referred to ground, the voltages E_1 and E_2 must similarly be referred to the ground point. This does not affect Equation (1), but Equation (2) becomes:

$$E_2 = -\frac{EZ_2}{Z_1+Z_2}$$

and,

$$E_o = \frac{E_1+E_2}{2} = \frac{E}{2}\left[\frac{Z_1-Z_2}{Z_1+Z_2}\right] \tag{4}$$

Equation (4) shows that when $Z_1 = Z_2$, the no flaw conditions, the output voltage E_o is null (zero). If a flaw is present under Coil Z_1 causing an increase in its impedance, the output voltage increases in a direction which we shall call positive. Conversely, if the tubing is moved so that the flaw is adjacent to the coil Z_2, the output voltage E_o becomes of negative polarity. When the flaw is midway between the coils $Z_1 = Z_2$, the output voltage is null or zero.

<u>Signal Injection</u>

Typically, the differentially connected inspection coils are wound (or connected) as shown to take advantage of aiding mutual inductance between the coils. The "aiding" connection increases coil sensitivity. The behavior of the static signal injection method depends greatly upon the coil polarity.

In the flaw detection case, the bridge imbalance results from relative charges in the AC impedance of the coils, whereas in the static injection case a bridge imbalance is caused by purposely induced AC voltages appearing in one or both coils. These voltages, indicated by symbols e_1 and e_2 in Figure 12 are induced by currents flowing in the injection coil. Relative polarities are indicated by the + and - symbols associated with e_1 and e_2. The change in polarity is a direct result of the different direction in which the coils are wound (or connected). It is noted that the relative polarity of the current flowing in the injection coil does not change when the injection coil passes through the inspection coil system, even though the current is varying at a sinusoidal rate in synchronism with the bridge excitation signal E. We shall assume that the bridge is balanced as in the no flaw situation, (thus $E_o = 0$) and we shall now consider the effect on the output voltage of the presence of any induced voltages e_1 and e_2. The shunting effect of the bridge drive transformer "T" is neglected in this discussion. This is justified because we are mostly interested here in polarity effects and not in actual amplitudes or sensitivities. The output signal E_o as a function of e_1 and e_2 is now:

$$E_o = \frac{e_1 + e_2}{2}$$

Thus, the polarity of the bridge imbalance is independent of which injection coil the injection coil is under. When the injection coil is between the inspection coils it can be expected, depending upon coil spacing and injection coil length, that the imbalance voltage might drop in amplitude.

If the inspection coils are wound, (or connected) to cause the mutual inductance between coils to be opposing the result is different. For example, if the inspection coil represented by Z_1 is now reversed the induced voltage e_1 (caused by injection coil current) is also reversed becoming $-e_1$. The bridge output then becomes

$$E_o = \frac{e_1 + e_2}{2}$$

The polarity of the output now depends upon which coil the injection coil is under. Indeed, when the injection coil is centered with respect to the inspection coils and the absolute values of e_1 and e_2 are equal the bridge output is zero. Thus, with the "mutual aiding" connection, a static injection signal causes a bridge imbalance having single polarity when the injection coil passes the inspection coils. In contrast, if the "mutual opposing" connection is used, the polarity of the bridge imbalance reverses as the injection coil traverses from one coil to the other.

COIL POSITION EFFECTS

The path taken by a static injection coil must be consistent to accurately reproduce a signal pattern. Variations in spacing or orientation can cause signal fluctuations due to changes in coil-to-coil coupling. Our laboratory experience has shown that this is not a serious difficulty. Consistent signal patterns have been reproduced with static injection coils with relative ease. The physical position and orientation of a dynamic injection coil also must remain constant with respect to the inspection coil, but this is not a problem since the coil normally is held in a fixed position.

The injection coils used consisted primarily of bobbin-type coils that were placed inside sections of the copper-nickel tubing. This allowed us to observe the effects of the tube upon the instrument response to injected signals. OD injection coils and probe-type coils were also used successfully. A typical ID injection coil is shown in Figure 13.

EXCITATION OF INJECTION COILS

Excitation of the injection coil is performed by active circuits operating at the same test frequency as the eddy current instrument. Static signal injection requires an excitation signal that has a fixed amplitude and phase relationship with the eddy current drive signal. Dynamic signal injection requires that the excitation signal vary in amplitude and phase according to a predetermined pattern. The circuitry employed in the laboratory for static and dynamic injection coil excitation is illustrated in Figure 14. A reference oscillator signal is obtained from the eddy current instrument to assure that the injected signal frequency will be identical with the eddy current inspection frequency and to avoid the possibility of interference from harmonics. The reference oscillator signal is adjusted in phase and amplitude by a combination of multiplying digital-to-analog (D-A) conversion circuits. The adjusted signal is then buffered and applied to the injection coil. The laboratory breadboard version of the signal injection circuitry is shown in Figure 15.

STATIC INJECTION

The multiplying D to A conversion technique permits convenient selection and adjustment of the amplitude and phase of the injected signal by digital input (binary) coding. In the static mode manually operated switches provide binary input codes to the multiplying D to A conversion circuits. The desired signal is obtained by properly adjusting the input codes. The phase and amplitude control possible with the static mode of signal injection is demonstrated by the pattern shown in Figure 16. Each excursion from the center of the pattern represents the eddy current instrument output

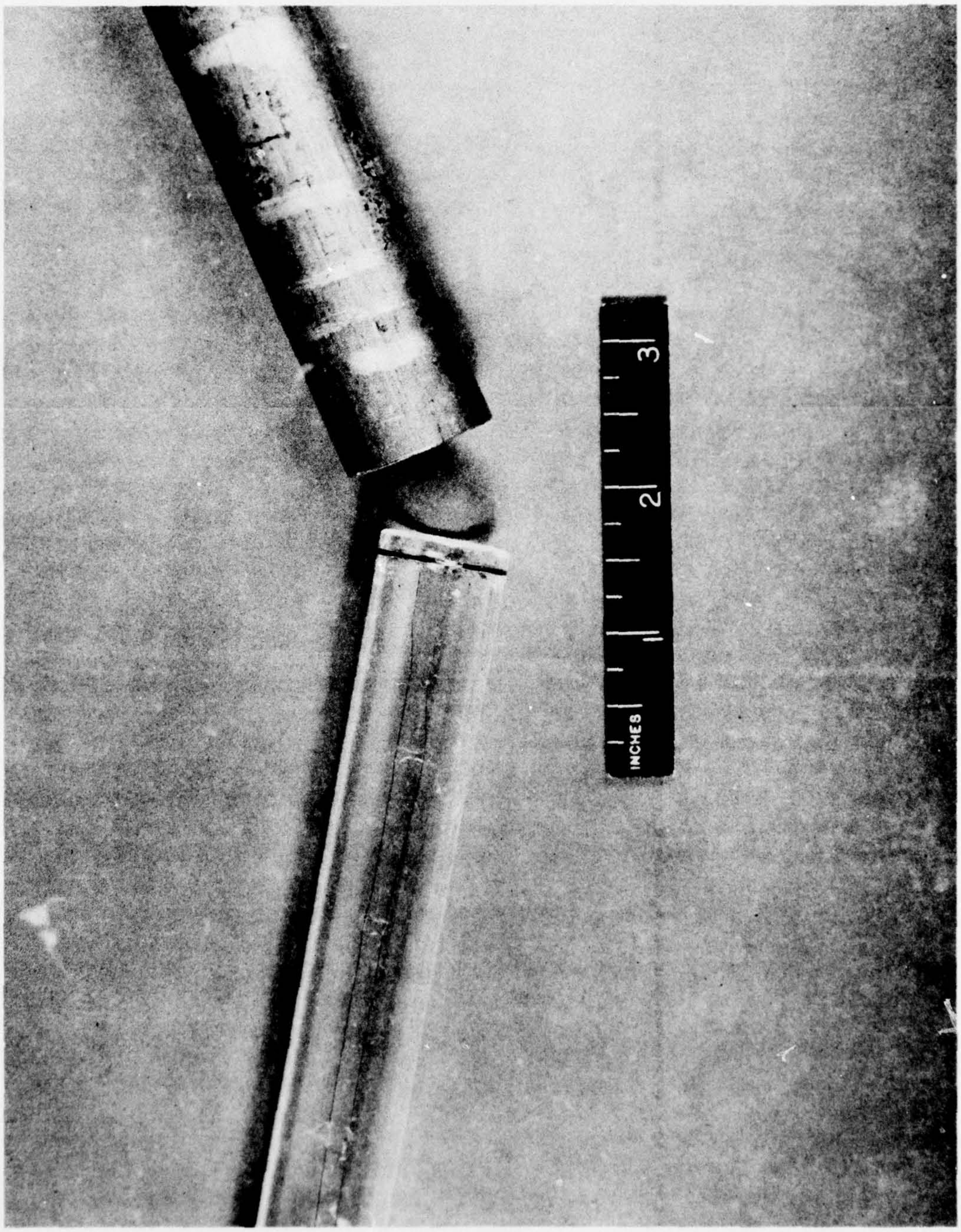


FIGURE 13. Photo of Signal Injection Coil

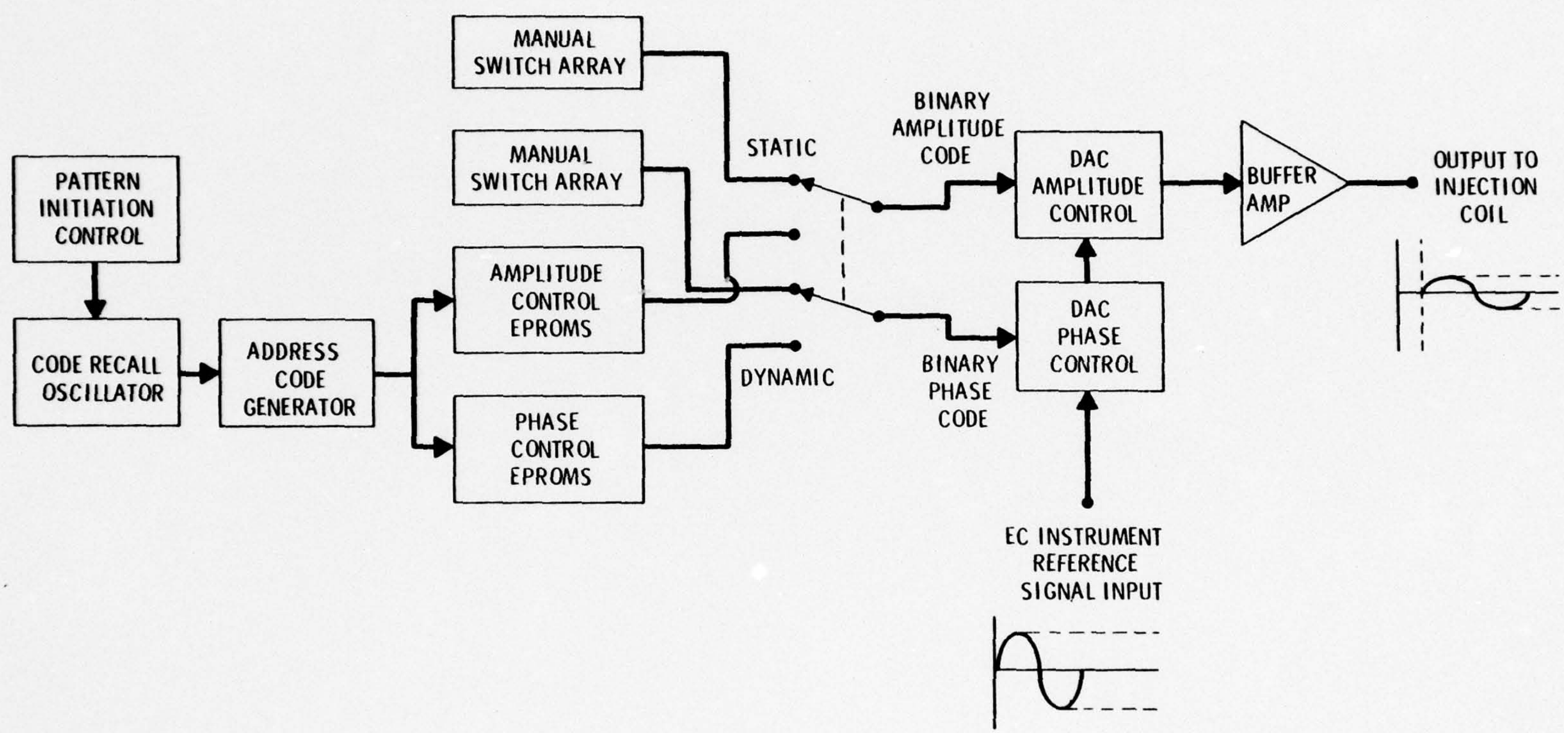


FIGURE 14. Signal Injection Circuit

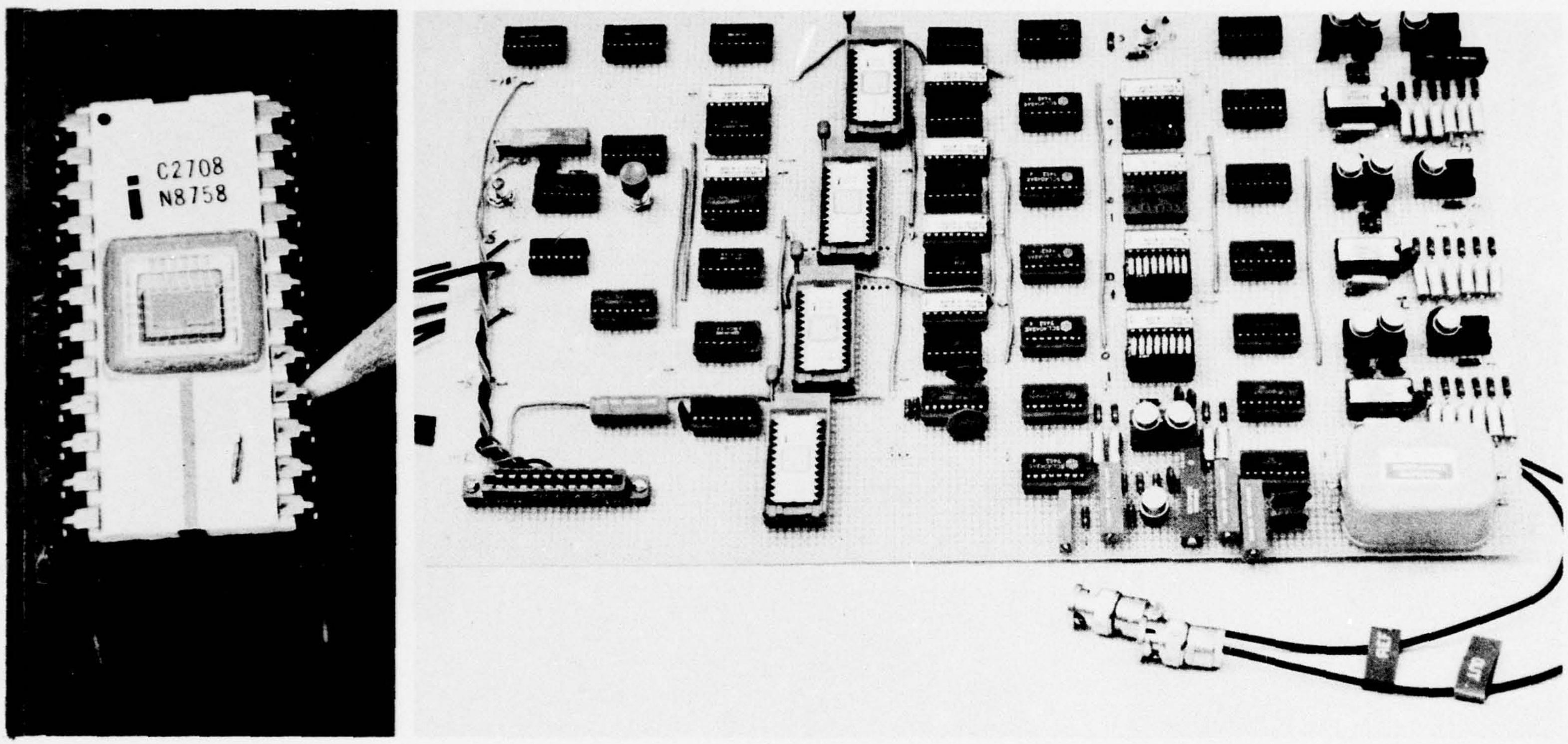


FIGURE 15. Laboratory Breadboard of Signal Injection Electronics System with Enlarged View of EPROM Semiconductor Memory

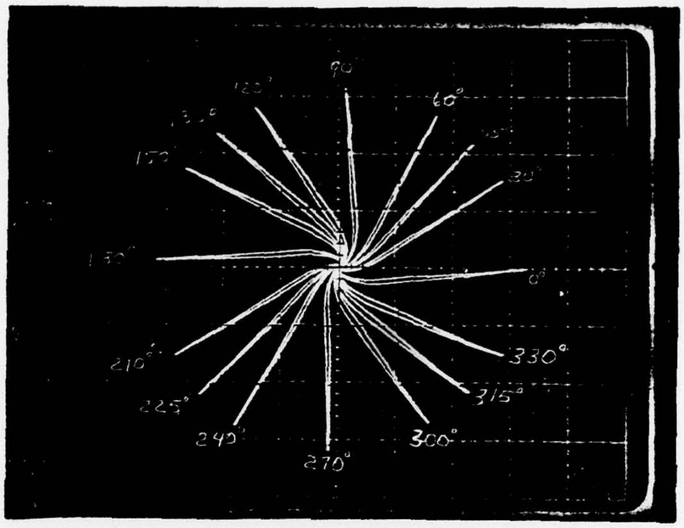


FIGURE 16. Eddy Current Instrument Response to Static Injection Signals

generated by passing an injection coil through the inspection coil (no tube present). The phase angle of the injected signal was adjusted after each pass to produce this composite storage CRT pattern. The end point of each trace is the peak injected signal amplitude which occurs at the point of maximum coupling between the inspection coil and the injection coil. The "open loop" effect is caused by a slight difference in the approach and leave curves. The slight curvature of each trace near the center of the pattern is characteristic of the inspection coil response to both machined flaws and injected signals. The static injection system can produce a signal excursion to any point on the impedance plane display for verification of proper instrument operation at that phase angle.

Figure 17A shows the absolute instrument response to an injection coil positioned inside a section of tubing being driven through the inspection coil (right trace). This signal pattern is very similar to the absolute instrument response to a longitudinal notch at a different location in the same tube (left trace). The injected signal closely resembles the artificial notch signal and may be substituted for the flaw signal for most calibration purposes. Drill hole patterns can also be simulated using the static injection technique. Figure 17B shows the absolute instrument response to a 5/64 in. drill hole (left trace) as compared to a static injection signal produced by an injection coil within the tube (right trace). Only minor differences are apparent.

DYNAMIC INJECTION

The primary benefit of using digital codes for analog signal control is in the generation of "dynamic" injection signals. In this mode, digital input codes stored in semiconductor memories provide the injected signal information. The memories are pre-programmed with the proper binary coding to produce a series of incremental changes in the phase and amplitude of the injected signal. The eddy current instrument output generated by this type of injected signal is a point-by-point retracing of a previously stored signal pattern. The relatively large storage capacity of the 8192 bit Intel 2708 erasable nonvolatile programmable read-only memories (EPROM's, shown in Figure 15) allows storage of up to 12 signal patterns

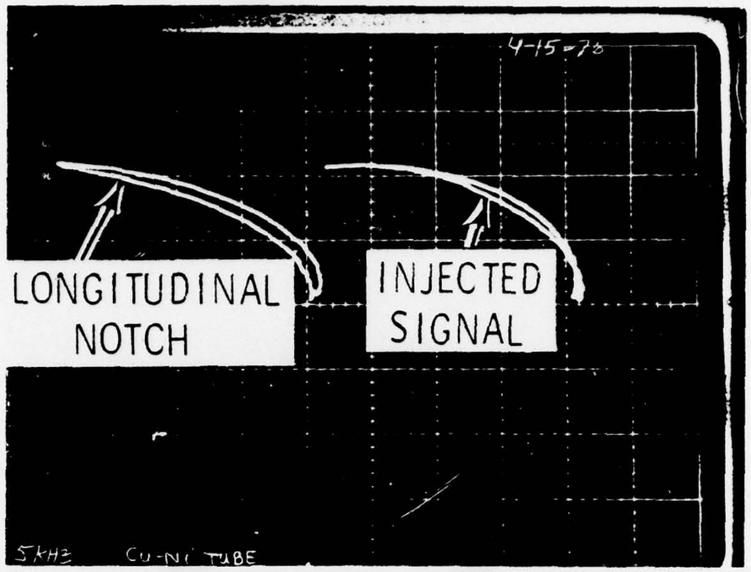


FIGURE 17A. Right Trace - Static Injected Signal
Left Trace - Longitudinal Notch (60%T deep)

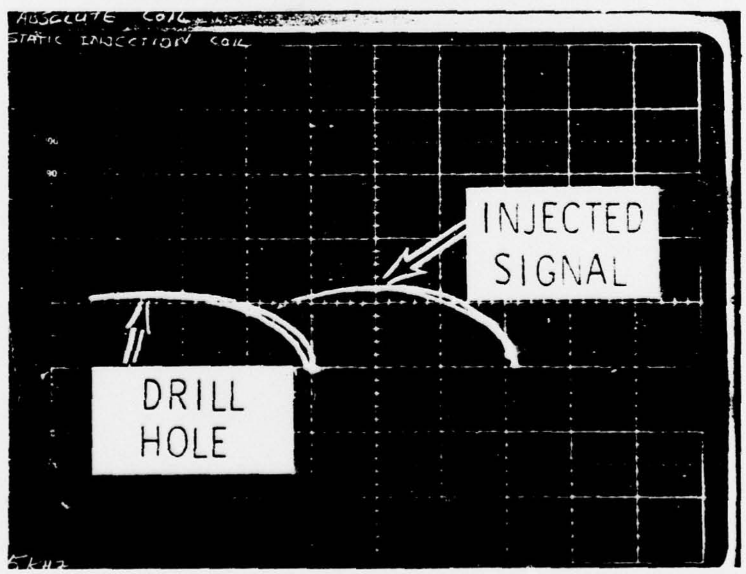


FIGURE 17B. Right Trace - Static Injected Signal
Left Trace - Drill Hole (5/64 in., 100%T)

FIGURE 17. Absolute Instrument Response to Injected Signals Compared to Tube Flaws

with approximately 85 incremental phase and amplitude adjustments per pattern. Reasonably good simulated signal patterns were obtained in the laboratory using only 50 incremental adjustments per pattern.

The digital signal codes are recalled from memory at a rate determined by the code-recall oscillator (see Figure 14). The rate of recall controls the speed at which the simulated patterns are reproduced and can be adjusted to duplicate actual flaw pattern speeds. Any one of the 12 possible signal patterns can be recalled individually or all patterns can be recalled in sequence.

The digital codes for each signal pattern are determined by using the "static" injection mode to manually make a point-by-point excursion around the desired signal pattern. The "digital" codes on the manual switches are recorded for each point and subsequently programmed into the appropriate memories using an EPROM programmer. The ease of duplication and erasable feature of EPROM make them very convenient for storage of the digital codes. The nonvolatile feature makes possible long-term storage of the information.

Dynamic injection circuitry reproduces differential (dual coil) instrument response patterns by recalling from memory the sequence of binary codes necessary to generate the desired signal pattern. The injected signal is applied to a coil located near the inspection coil. Figure 18A shows the differential instrument response to a naturally occurring flaw (subsequently identified as an OD longitudinal flaw) in a section of copper-nickel tubing. The dynamically injected pattern at left is a near duplicate of the actual flaw pattern. The injected pattern was generated by programming the injection system to follow approximately 50 points around the original flaw pattern. The storage oscilloscope beam generated a continuous trace on the CRT screen.

The dynamic signal injection memory can be programmed to reproduce virtually any flaw signal pattern desired. Another example is shown in Figure 18B. The right trace is pattern caused by a 5/64 in. ID hole (36% T) inside a section of tubing. The left trace is the dynamically injected reproduction of the flaw pattern. These dynamically reproduced patterns, shown in Figures 18A and 18B, could replace artificially produced flaws in tubing for calibration and adjustment of eddy current instruments.

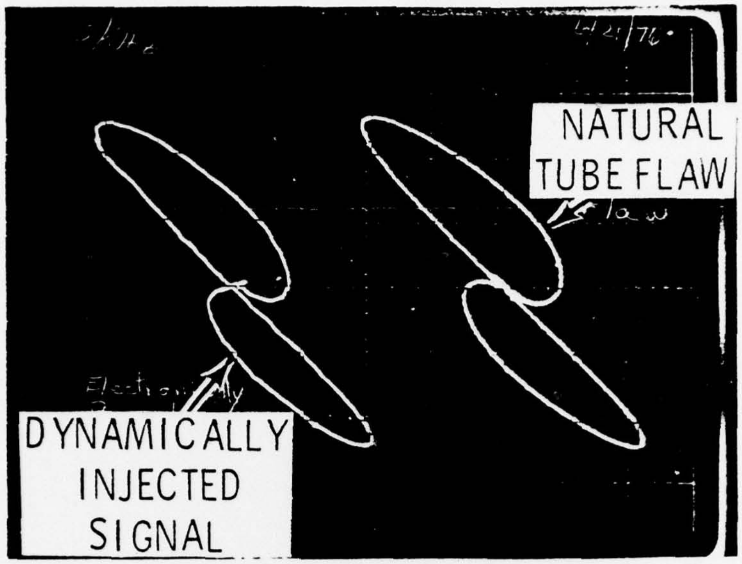


FIGURE 18A. Left Trace - Dynamically Injected Signal
Right Trace - Natural Tube Flaw
(test frequency - 5 kHz)

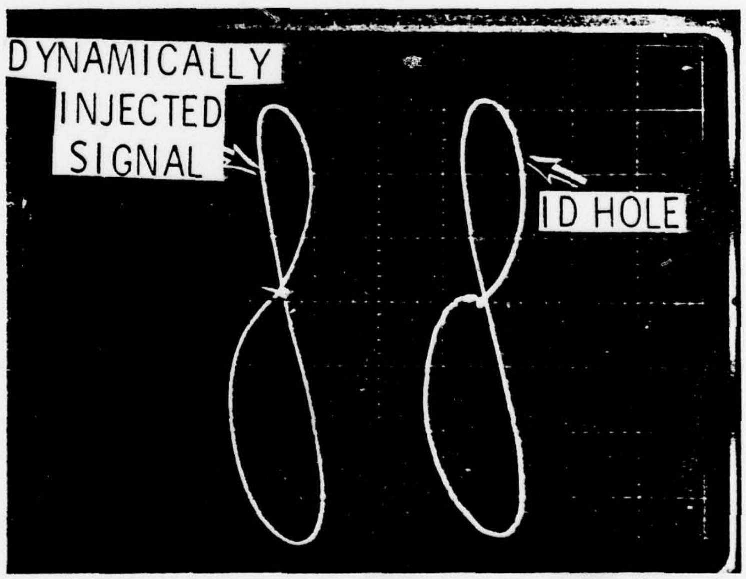


FIGURE 18B. Left Trace - Dynamically Injected Signal
Right Trace - ID Hole Signal (5/64 in. diam, 36%)
(test frequency = 20 kHz)

FIGURE 18. Differential Instrument Response to Injected Signals Compared to Tube Flaws

CONCLUSIONS AND RECOMMENDATIONS

Artificially generated signal patterns provide an alternative to fabricated flaws for producing eddy current calibration signals. Signal injection and passive signal generation techniques can provide the variety of signal patterns necessary for confirmation of proper operation and calibration of the eddy current instrument under all anticipated inspection conditions. Signal injection techniques can duplicate actual flaw patterns and passive loading coils or metallic tabs closely simulate many typical flaw patterns. Signal injection coils can be incorporated into inspection coil assemblies to permit periodic recall of calibration data during or between inspections.

Dynamic signal injection is particularly versatile in that virtually any signal pattern can be generated by properly programming the semiconductor memories. The programmed information is stored indefinitely or until intentionally erased. Complete libraries of program data or memory devices can be accumulated to accommodate particular test conditions or test criteria, such as tube material, size, nominal wall thickness, and flaw types. The memories are easily duplicated with conventional PROM programmers at a small cost in comparison to fabrication of machined flaw standards.

Metallic tabs and passive loading coils are also attractive alternatives to machined flaws. Metal tabs provide a good variety of signal patterns for calibration purposes and can be mounted on nonmetallic forms to permit ease of handling and use. The signal pattern amplitude and phase angle control that is possible with loading coils using passive electrical components presents some interesting possibilities for switching arrangements to generate complete sets of calibration signal patterns. Neither tabs nor loading coils contain active circuitry or require reference signals from the test instrument which makes them more adaptable to a variety of instrument designs. This is in contrast to the signal injection circuitry which must be tailored to a specific instrument design although the readjustments necessary to accommodate most instrument designs are relatively minor.

The flexibility and versatility of the dynamic signal injection technique offers significant improvement over existing calibration procedures and techniques. We recommend that future programs be directed toward development and fabrication of a field demonstration prototype signal injection system. The prototype system should be incorporated into a field inspection system to demonstrate the usefulness and advantages of the signal injection technique. Development of a field demonstration prototype will require fabrication and packaging of the injection circuitry to interface with a commercially available eddy current inspection instrument. Field evaluation of the system would provide a proof-in-practice demonstration of the signal injection technique.

Another aspect of signal injection that should be investigated is the development of an automatic memory programming technique. Automated memory programming would significantly simplify the laboratory procedure required to establish the digital memory code now obtained by a tedious manual technique. Automated programming will require development of specialized circuitry that could program memories to reproduce any flaw pattern by simply passing the flawed specimen through the inspection coil. An automated system would substantially reduce the time involved in programming the original flaw information in the memories.

Development of the signal injection technique could lead to better eddy current calibration techniques and therefore more uniform eddy current inspection of procurred tubing.

REFERENCES

1. Libby, H.L.,"Miscellaneous Eddy Current Techniques", BNWL-996, Battelle-Northwest, Richland, WA, January 1969, pp. 17-20.

2. Ord, R.N. and Richardson, R.L.,"Eddy Current Test Pattern Recognition Program", BNWL-942, Battelle-Northwest, Richland, WA, November 1968.

3. Libby, H.L., Introduction to Electromagnetic Nondestructive Test Methods, Wiley - Interscience, New York, NY, 1971.

4. McMaster, R.C. (Ed.), Nondestructive Testing Handbook, Vol. 2, Ronald, New York, 1959.

5. Military Specification for 70-30 and 90-10 Copper Nickel Alloy Condenser and Heat Exchanger Tubing, MIL-T-15005E, July 1962.

6. Evaluation of Computer Simulated Signals System or Metallic Tab for Standardizing Eddy Current Inspection Systems", Battelle-Northwest proposal to Naval Ship Engineering Center, Hyattsville, MD., BNW Proposal No. 2311102136, Battelle-Northwest, Richland, WA, April 1974.

7. Crowe, J.C., "Calibration of Eddy Current Systems with Simulated Signals", BN-SA-615, Battelle-Northwest, Richland, WA, September 1976.