ELECTROMAGNETIC
(EDDY CURRENT)
NONDESTRUCTIVE TESTING
OF
NONFERROUS
METAL
TUBINGS AND RODS

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NONDESTUCTIVE TESTING
OF
NONFERROUS METAL TUBES AND RODS

By

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CONTENTS

ABSTRACT

In this thesis,nondestructive testing of nonferrous metal tubings and rods has been investigated by employing eddy currents.

Especially the detection of cracks within the metal bodies and on the surfaces,electromagnetic induction, signal processing,and other problems of testing procedure have been examined.

A multifrequency test device has been realised by using discrete components and operational amplifiers to examine aluminium tubes and rods.

OZETÇE

Bu tezde manyetik olmayan metal tüp ve çubukların tahribatsız kontrolları,eddy akımları kullanarak araştırılmıştır.

Özellikle,metal gövdelerindeki ve yüzeylerindeki çatlak saptamaları,elektromanyetik etkileme,sinyal değerlendirmesi ve diğer kontrol sorunları üzerinde çalışılmıştır.

Ayrık bileşenler ve işlemsel kuvvetlendiriciler kullanılarak,alüminyum tüp ve çubukları kontrol eden çok frekanslı bir alet gerçekleştirilmiştir.

CHAPTER-I

INTRODUCTION

Electromagnetic nondestructive test methods are widely used in the metals industry to solve a variety of materials and product evaluation problems.Nondestructive tests are used to inspect and evaluate materials,parts,and other products in ways that do not adversely affect their serviceability.Other much used nondestructive tests are based on principles of radiography,ultrasonics,magnetic particles,and dye penetrants.The principle of the electromagnetic test is that electromagnetic field perturbations caused by the presence of a test object in the field are measured and used indirectly to detect conditions of interest in the test object.

The most commonly used nondestructive test applying electromagtism is the EDDY CURRENT TEST.Other tests are magnetic field tests using electromagnetic induction sensors,magnetic field leakage tests using electromagnetic induction sensors,and radiofrequency and microwave tests involving radiation fields.

The main operational functions common to most electromagnetic tests are:(a)the excitation of one or more test coils to produce an electromagnetic field within the test object,(b)the modulation of the electromagnetic field quantities by the test object,(c)the preparation of test coil output signals for analysis,(d)the analysis of the test coil output signals,and (e)the display or indication of the test results of the analysis.

1.1 Nature and Uses

Electromagnetic test methods use magnetism developed by the flow of currents.Usually a periodically varying current is impressed upon one or more inductors or coils,which produces a varying magnetic field within the test object.This magnetic field is modified by one or more electrical conditions of the test object such as electric conductivity,magnetic permeability,or electric permittivity.The magnetic field is monitored by measuring or analysing the resulting induced voltages or currents or both in exciting or sensing coils. The eddy current nondestructive test utilizes the effect of test object electric conductivity and,in addition,in the case of magnetic materials,the effect of test object magnetic permeability.

MAIN PRINCIPLES.The principle of the electromagnetic nondestructive test applied to inspect metal tubing is illustrated in Fig.1.1.

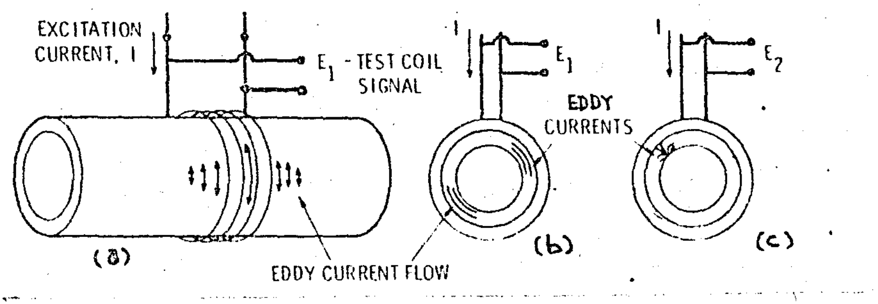


Fig.1.1 Tubing test using a single encirciling coil:(a)Side view,(b)current distribution,normal uniform tubing,cross-sectional view,(c)current distribution,tubing with crack,cross-sectional view.

Eddy currents are caused to flow within the test object by electromagnetic induction.A sinusoidal constant amplitude current is impressed upon the single test coil,as shown in Fig.I.Ia.This produces a varying magnetic field,causing eddy currents to flow in the tubing in the vicinity of the coil.In normal,uniform tubing these currents flow in concentric paths around the tube wall,as shown in the cross-sectional view in Fig.I.Ib.These currents produce a field,called the secondary field,which adds vectorially to the primary field. The combined fields produce,by electromagnetic induction,a voltage signal E_1 at the test coil terminals.A crack in the tube alters the flow path of the eddy currents approximately as shown in Fig. I.1c, resulting in a new test coil voltage E_2 ,thus,the signal voltage across the test coil varies with test object conditions.The signal voltage also varies with test coil-to-object electromagnetic coupling.This test signal is an ac signal having the same frequency as that of the test coil excitation current.It is modulated by the changing conditions of the test object within the test coil field. This signal,being sinusoidal,can be described by an amplitude value and a phase angle value with reference to the test coil exciting current.

It is assumed that the excitation current has a fixed value and that the information signal appears as changes in the voltage across the coil.This is a convenient method for explaining the behaviour of the test coil-test object system,but it does not represent the only way to view this system.Since the electric impedance of the test coil is equal to the ratio of the coil voltage to the currents flowing in the coil,it is apparent that the test coil impedance varies with the test object condition.This method of analysing the test coil output signals is referred as "Impedance Analysis",(I).

In another method of monitoring the electromagnetic field the Hall detector,a semiconductor element,is used.The Hall device produces an output emf which is proportional to the product of the electromagnetic field intensity and a biasing current, (2).

The eddy currents,in the absence of test object irregularities, flow parallel with the surface and in a direction generally determined by the test coil.Irregularities to be detected must interfere with the flow of currents.For example,a crack oriented with its plane perpendicular to the eddy current flow gives a larger signal than if its plane is parallel with the current flow.An infinitesimall thin lamination in the direction of current flow would have only an infinitesimal effect on the current flow.

FREQUENCY SPECTRUM.The electromagnetic tests,including the eddy current tests,usually use alternating currents and occupy the region of the spectrum extending from low frequencies into the microwave regions (10^{8}-10^{12}Hz).Most of these tests operate in the region from 500 to 500,000 Hz.However,radiation and dielectric effects become increasingly important as operating frequencies are increased toward the microwave region.

USES.Electromagnetic nondestructive test methods are used in industry to inspect and evaluate a variety of materials and products Employed mainly for the inspection and evaluation of electrically conducting materials,the tests can be performed rapidly and usually require no electrical contact with the test objects.Beside the detection of cracks,a wide range of measurements can be made including foil,plate,and tubing thickness,rod and tubing diameter, electric conductivity,plating thickness,and the thickness of nonmetallic coatings on metallic bases.

Electromagnetic tests are most sensitive to conditions near the surface of the test object nearest the test coil because of the skin effect.This effect,the result of mutual interaction of the currents,increases with the increase in the operating frequency, test object electric conductivity,or test object magnetic permeabil

The electromagnetic test is especially sensitive to variations i magnetic permeability of materials.This is an advantage for monitoring purposes of magnetic permeability which may be related to product serviceability.However,the high sensitivity of the test to magnetic permeability variations can result in signals which mask those caused by other conditions of greater interest.A magnetic saturation technique can be used to reduce this interference to an acceptable level.

CHAPTER-2

BASIC PRINCIPLES

Electromagnetic induction is one of the key principles of the electromagnetic test.Electromagnetic effects are caused within the test object by varying electromagnetic fields.This results in eddy current flow in a metal test object.The current flow within the test object sets up a secondary magnetic field which causes electric signals within the test coil that are related to test object electrical conditions.Both electrical and magnetic characteristics of the test object are important.Eddy current flow within the test object results in the skin effect,a concentration of the currents toward the surfaces adjacent to the exciting test coils.

2.I Electromagnetic Induction

For electromagnetic induction,the test object is placed in a varying magnetic field,called the primary field,set up by currents flowing through a test coil.Varying currents are induced in the electrically conducting test object by this varying magnetic field.These currents whose flow depends upon the test object variables themselves, produce a varying magnetic field.This magnetic field associated with the test object is called the secondary field.The principles are illustrated in an approximate way by Fig.2.I.The test coil without the test object is shown in Fig.2.Ia.An alternating current I produces a primary field H_p.Next an electrically conducting test object is placed in the field of the coil,as shown in Fig.2.Ib.The induced eddy currents flowing in the test object produce a secondary field H_s,which,in the case of nonmagnetic test objects,opposes a primary field to an extent that depends on the conductivity,size of the object,and operating test frequency.The timing or electrical phase angle of the induced eddy currents varies,depending upon the test object parameters and the test frequency.The secondary field associated with these currents also varies similarly.This secondary field is monitored by observing its effects on the current or voltage of the primary test coil,or upon currents or voltages induced in one or more sensing coils placed nearby.Actually,the effects of the primary fields are also monitored,but,as the primary field can be made constant,its effects can be cancelled.

The relative phase angles of the excitation current,magnetic flux and coil voltages are important.Fig.2.2 illustrates these relationships in a single test coil first without the test object and then with the test object within the coil.The conditions for the test coil without test objects are shown in Fig.2.2a.Here the

Fig.2.1 Main principle of the eddy current test:
(a)empty coil with primary magnetic field,(b)test object within coil,producing a secondary field.

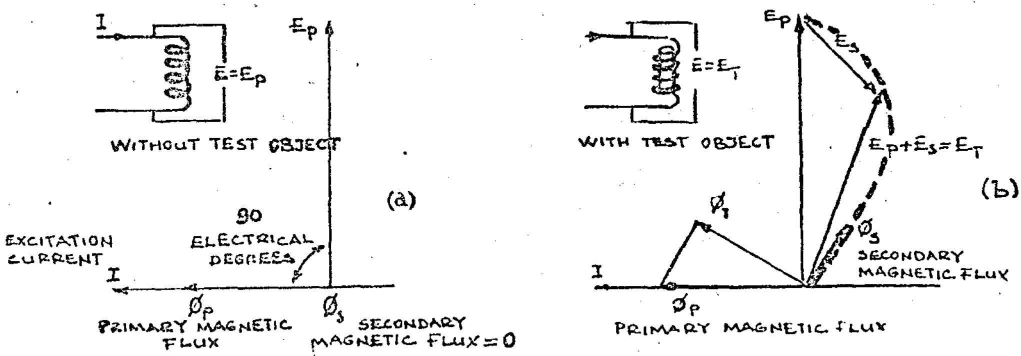


Fig.2.2 Current and magnetic field phase angles:
(a)Without test object,(b)with test object.

primary magnetic flux $\O_p$ is in phase with the excitation current I. No secondary magnetic flux is seen because no test object within the field of the coil.In this case the voltage developed across the test coil lags the excitation current by an angle of 90 degrees.These diagrams are drawn with lagging phase angles shown increasing in the clockwise direction.In these diagrams the direction of the lines represents the phase angle,and the length of the line represents relative amplitudes.

When the test object is placed within the test coil,as in Fig. 2.2b,eddy currents flow and a secondary magnetic flux is established.In this particular case,it is assumed that the secondary magnetic flux ϕ_s is produced.This secondary magnetic flux gives a new total flux ϕ_t.This new total flux ϕ_t produces a new test coil voltage E_t which lags ϕ_t by 90 degrees.The same result is obtained by considering the fluxes to operate separately,producing their own associated induced voltages.For example,the primary flux ϕ_p can be considered to produce the voltage E_p and secondary flux ϕ_s can be considered to produce the voltage E_s lags it by 90 degrees.By adding E_s to E_p,as shown,the net coil voltage E_t is again obtained.The test coil voltage resulting from the presence of the test object is actually E_s.However,this voltage is not directly available.It can be made available by subtracting from E_t a fixed voltage equal in amplitude and phase to the voltage E_p.

Any line between two points on the diagram represents a sinusoidal signal having an amplitude proportional to the distance between the two points and a phase angle described by the slope of the line.Also,we are not restricted to the use of the original orign as a reference point.Any other point on the diagram can be used as a new reference point.The signals on the diagram viewed from the new reference point are represented by phasors drawn from the new reference point to each of signals,that is,to the heads of the phasors representing those signals.These new phasors re -

present the amplitudes and phase angles of the signals viewed from the new reference.Likewise,the horizontal base line,can be replaced by any other line through the origin,taking into account the difference in the phase angle of the original reference and the new reference.This flexibility of the phasor diagram is useful in representing and visualizing the various signals involved in compensating or null balance circuits,which are often used in the input circuits of electromagnetic testing equipment.

By using phasors,various universal loci diagrams have been obtained for different application purposes.These loci diagrams are used to determine coupling effects,effect of frequency changes, conductivity,magnetic permeability,thickness of one or more number of layers by observing the changes in resistive and reactive parts of the impedance of the test coils,(I),(4),(5).

2.2 Eddy Current Flow and Skin Effect

One result of the flow of eddy currents in the test object is the skin effect.It causes the currents to be concentrated near the surfaces adjacent to the excitation coils.The effect increases with the increase in operating frequency,test object electric conductivity,and magnetic permeability.The currents decrease exponentially with depth,depending upon the test object shape and thickness.In addition to the decrease of current amplitude as depth below the surface increases, the phase angle of the current becomes increasingly lagging.

The skin effect can be explained in several different but related ways.One explanation shows that eddy currents flowing in the test object at any depth produce magnetic fields at greater depths which oppose the primary field,thus reducing its effects and causing a decrease in current flow as depth increases.Another explanation considers the skin effect a result of the absorption of energy from an electromagnetic wave as it propagates in the metal.The skin effect can be described by an infinite half-space conductor upon which impinges a plane wave of infinite extent with magnetic field parallel with the surface of the conductor.The value J_x,the current density at any depth x from the surface,is given by

$$J_x = J_o \exp(-x\sqrt{\pi f \mu \sigma}) \qquad (2.I)$$

where J_o:current density at surface, A/m^2

f :operating frequency, Hz

μ:magnetic permeability

$\mu = 4\pi \times IO^{-7}$ H/m for nonmagnetic materials

For magnetic materials:

$$\mu = \mu_r \mu_o$$

Where μ_r:relative permeability

$\mu_o = 4\pi \times IO^{-7}$ H/m,the magnetic permeability of free space

x :depth from surface.Meters

σ:electric conductivity.(Mhos/Meter) S

The depths at which eddy current density has decreased to I/e times its value at the surface is called the penetration depth. Equation 2.I may be written

$$J_x = J_o \exp(-x/\delta) \qquad (2.2)$$

where $\delta = I/\sqrt{\pi f \mu \sigma}$:penetration depth of eddy currents.

The phase angle lag,using the phase angle of the current density at the surface as a reference angle,is given by

$$\theta = x \cdot \sqrt{\pi f \mu \sigma} = x/\delta \qquad (2.3)$$

where θ:phase angle lags.Radians

2.3 Selection of Frequency

Two main factors affecting the selection of test frequency are the skin effect and the effectiveness of coupling energy into the test specimen.Generally,the effectiveness of coupling energy into the test object increases as the frequency is increased.Since the skin effect results in current concentrations near the surface adjacent to the exciting sources or test coils,deep penetration of currents requires lower-frequency operation for fixed test specimen conductivity.However,the eddy current density at a fixed frequency also becomes less with depth increase in the cylindrical test specimen because of the smaller loops of emfs available as the center of the bar is approached.This occurs no matter how low the test frequencies are made.If it is desired to detect conditions at some depth within a bar,a high frequency is not chosen because insufficient current would flow at the desired depth.Improved operation results as the frequency is lowered ,but eventually diminishing advantages result with further lowering of the test frequency because of the ineffectiveness of the energy coupling into the test object and the falling off of currents because of the shape of the test coil and test object.When tubes are inspected using the cylindrical coil arrangement,it is found that the eddy current density does not fall off as rapidly with depth into the tube wall as it does in the case of the solid bar.Thus,higher test frequencies can be used for the inspection of tubes than is indicated by considering the skin depth equations alone. (3)

CHAPTER-3

INSTRUMENTATION

3.I Instrumentation Concepts

Electromagnetic nondestructive test systems perform the following important functions:Excitation,modulation,signal preparation,signal analysis,signal indication,and test object handling.

Excitation is performed by generator which delivers the excitation signal to the test coils.The generator may consist of single frequency or multiple frequency sinusoidal oscillators and power amplifier circuits.It may also be a pulse generator delivering the desired pulses.A self-excited oscillator whose behaviour is governed by the impedance of the test coil may also be used.

The modulation of signal occurs in the electromagnetic field of the test coil systemThe test coil system may be in some different configurations which is often closely related mechanically to the test object handling equipment.

The signal preparation part consists of circuits which prepare the output signals from the test coil for the (next) analysis section.These circuits consist of ac compensating or balance networks which subtract a steady ac component from the input signal so that the instrument amplifiers do not need as large a dynamic range as otherwise would be the case.In this part of the system filters can be used in order to signal-to-noise ratio or to separate different carrier signals in a multifrequency test system.Sometimes some signal-shaping circuits are included.The amplifiers,which are the important parts of this portion,raise the signal to the desired level for the analysis process.

The demodulation and analysis section of the system comprises detectors and analysers.The detectors may be either amplitude detectors or amplitude-phase detectors.For detectors,reference signals are provided from the generator sections.Sampling circuits and discriminators may also be included in the analysis section.Various types of summing and comparison circuits may also be used here.Filters may also be included for filtering the demodulated signal to discriminate against certain characteristics of the signal.

The signal display of indication portion of the equipment is the real link between the test equipment and its intended purpose.The signal may be displayed by the use of meters,recorders,cathode-ray oscilloscopes,visuable or audible alarm signals, relay outputs,and automatic signalling or reject equipment.

Test object handling equipment needs may be minimal or may require very comlicated mechanical design.In some tests the test coil assemblies are designed so that they are positioned and held manually.In this case the demands for test object handling equipment are minimum,and all that is required is a place to set or hold the test object while it is being inspected.

As it is seen,the test system circuits vary greatly,depending upon applications.An ac bridge circuit is shown in Fig.3.Ia

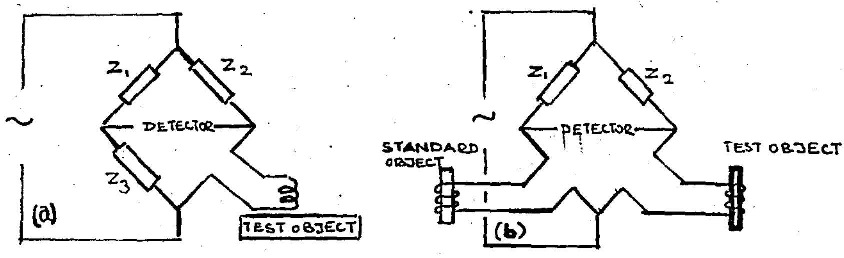


Fig.3.I Test coil bridge circuits:(a)single test coil,(b)two coil comparison test.

In this figure the test coil is used as one arm of an ac bridge. The bridge can be balanced for a normal test object,and the indicator then shows when a test object is present which does not fall within acceptable limits.

Another variation of this circuit is shown in Fig.3.Ib.Here another test coil has been added in one of the other arms of the bridge,resulting in a comparison arrangement.In this case standard test objects are first placed in each of the two coils and the bridge is balanced.Then one of the test objects is replaced by an unknown test object and differences between the unknown test object and the standard are indicated by the degree of unbalance of the bridge.

Multifrequency electromagnetic nondestructive test equipment may be divided into two classes:those which use one test frequency at a time and those which use more than one frequency simultaneously to perform the tests.

A functional diagram of a multifrequency equipment which uses several frequencies simultaneously is shown in Fig.3.2.Excitation currents at each test frequency are impressed upon the test coil simultaneously.Multiple circuits are used throughout,and the test coil output signal carrier frequencies are separated by filters. Multiple dual-amplitude phase detectors are used,and the outputs of the phase detectors are summed and used to give separation of several test object parameters.

MODES OF OPERATION.The test equipment may be classified by mode of operation.This depends mainly upon two functional areas. The first is concerned with the type of test coil excitation and the second with the degree of compensation or nulling of the test coil output signal and the type of the detector used.Types of excitation include single-frequency sinusoidal,multiple frequency, single pulse,repetitive pulse,and swept frequency.

Three main input-detector modes are:

I.Null balance with amplitude detector

2.Null balance with amplitude-phase detectors

3.Selected off-null balance with amplitude detector.

The second mode,which will be employed in our design,uses the null balance condition with amplitude-phase detectors.Here the phase discrimination method can be applied to discriminate against signals having a particular phase angle.Also,with this system the total demodulated signal can be displayed on the oscilloscope to show phase relations and amplitude relations,thus giving more meaning to the test object signals than in the case with systems which are not phase-sensitive.The display system does require the output signals from two phase detectors and their associated phase reference systems.

3.2 Test Coil Systems-Modulation Function

The modulation function is carried out within the test coil-test object complex.The test coil assembly is the link with the test object and its design is a major factor in the distribution of electromagnetic fields within the test object.The orientation of the test coils determines the direction of flow of eddy currents within the test object.

A wide variety of test coil configurations are possible. Although individual test coils can be used,double coils can also be used to perform an almost equivalent function.This is illustrated by the two coil arrangement shown in Fig.3.3,where the primary field is established by an excitation winding.The test coil output signal is taken from the output of the second winding, which is called the sensing coil.When the sensing coil is placed near the excitation coil almost the same magnetic flux threads both coils,thus the signal of either coil can be used to provide information about the test object.The use of the two-coil assembly provides greater flexibility in that the excitation winding can be designed to be driven from a low impedance source,and the sensing coil can consist of a greater number of turns to better match to a higher impedance instrument input circuit.

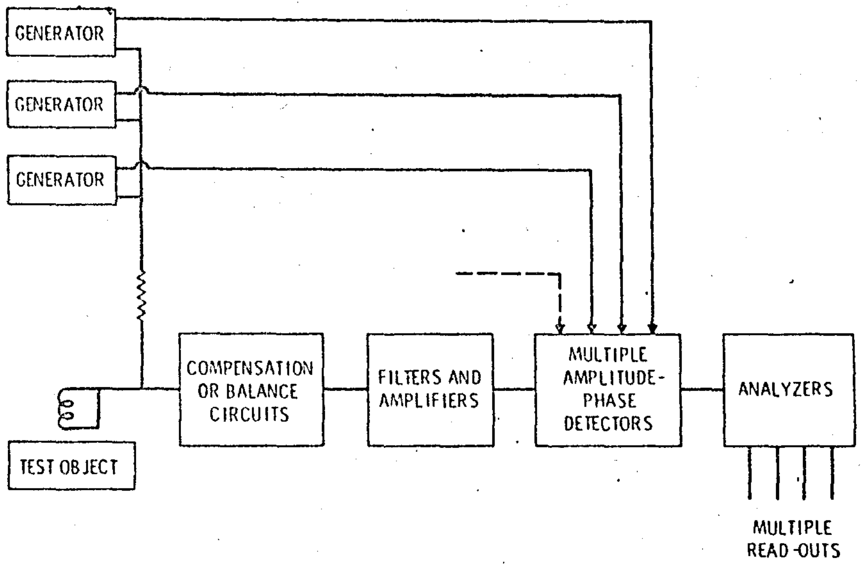


Fig.3.2 Multifrequency instrument operating at several frequencies simultaneously.

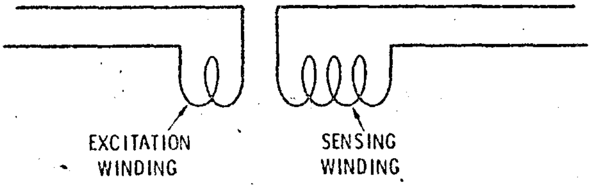


Fig.3.3 Double coil assembly.

Test coils may be shielded with conducting metal or magnetic material to shape the field produced by them or to increase the sensitivity or the resolution.Probe coils may have magnetic cores or may be wound in magnetic cup cores.

The single coil is shown in Fig.3.4a

Using such a coil,conductivity measurements and dimensional measurements can be made.In the differential arrangement shown

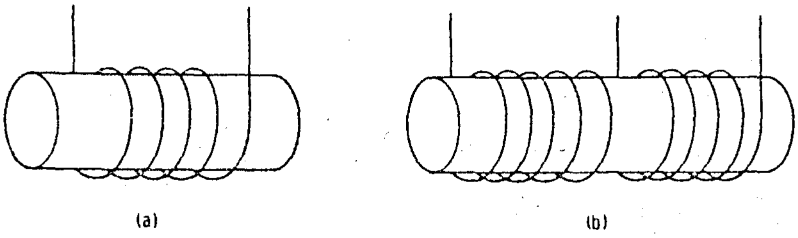


Fig.3.4 (a)Encirciling coil,(b)Encirciling differential test coil.

in Fig.3.4b,the coils are connected in a bridge circuit so that a null signal is obtained if each coil is presented to it identical test object conditions.Only when a different condition is presented to one coil or the other an output signal is obtained.Thus ,this coil arrangement can be used to discriminate against slowly varying conditions along a section of tubing or bar.The slowly varying diameter or wall thickness variations can be discriminated against whereas short localized cracks or other local wall conditions can be detected.

The resolution characteristic of a coil increases as its size is decreased.Generally,a probe coil can be made to have better resolution than an encirciling coil.The advantage of the encirciling coil in the testing of tubing is that a high output can be achieved because the tubing can be passed through the coil rapidly.The use of a probe coil to examine tubing requires a scanning motion.This can be obtained by either rotating the tubing and translating it past the probe coil or by translating the tube through a coil assembly which rotates the probe coil around the tube.This latter arrangement is called as spinning probe.

Important test coil characteristics are resolution,sensitivity, impedance,mechanical stability,size,distributed capacitance,and mounting arrangement.

3.3 Input Circuits-Signal Preparation Function.

The main functions of the input circuit are threefold.First,it provides,when needed,an adjustable compensating or nulling signal for compensating a fixed component of the test coil output signal. This results in the application of a smaller total signal to the amplifiers and detectors or it provides a signal of desired phase and amplitude.Second,it provides filtering for separating carriers having different frequencies,as in multifrequency test,or it provides filtering for reducing the bandwidth for noise reduction purposes.Third,it provides low noise amplification of test coil output signals or the output of the compensating circuit or filter circuits.All these functions are carried out as needed to fulfil the detector analyzer input requirements.

3.4 Detectors-Analysis Function

The purpose of the detector is to demodulate the carrier signal which has the test object information contained in its amplitude, phase,or frequency variations.In some equipment,the detector provides all the analysis function that is performed,in other equipment additional analysis functions are carried out by circuits following the detector.Post-detector filtering and amplitude discriminations are also part of the signal analysis function.Many types of detectors are used.A few of these are amplitude detectors, amplitude-phase detectors,phase angle detectors,and sampling detectors

3.5 Indicators-Display Function

Display and indicator needs differ greatly,depending upon the applications of the test,requirements for permanent records,and demand for automatic control features.Automatic,visual,or audible alarms can be included in the indicator equipment.Bar and tube test equipment is sometimes equipped with pen markers for marking flaw indication locations on the tube or bar.

3.6 Test Object Handling Equipment.

Test objects may be large and heavy or small and many.Equipment using hand-held probes usually presents the fewest test object handling problems.However,means must be available for bringing the test object to the instrument,or in the case of portable instruments the test object must be accesible and available for the test.Bars and tubes can be fed through encirciling coils by means of a roller fed assembly.A large unwanted signal is caused when the ends of the tubing enter or leave the test coil.This can be eliminated by using photocell detectors,mechanical switches, or proximity detectors to prevent false indications.

CHAPTER-4

MULTIFREQUENCY METHOD

The parameter separating capability can be increased by increasing the number of test frequencies.However,in doing this several importan questions arise.For example,are the functions obtained independent so that the variables may be separated?What technique can be used to separate these desired signals?These and some other related topics are discussed in this chapter.

4.I Need for Multivariable or Multiparameter Methods

Two complementary factors highlight the need for improved nondestructive test which will identify additional test variables:

I.The manufacture and application of new materials and products resulting from advances in science and technology require improved test methods.

2.The electromagnetic nondestructive test has multivariable capabilities which have not been fully developed.

One approach to meet needs which may involve several test variable is to use multifrequency methods.These methods are generally still in the research and development stage,but they show capability of perfor mance beyond that which can be obtained using single frequency techniques.

Most eddy current tests are made using one test carrier frequency at a time.These tests have been highly developed over a long period and serve many testing needs well.The new multiparameter or multivari able tests require more complex equipment and,in their present state of development,more difficult operating procedures than the simpler single-frequency tests.The new tests are expected to meet needs in special problem areas where the nature and importance of problems will justify the added comlexity and cost.

4.2 Multiparameter Test Theory

The nondestructive test variables which we wish to identify or separate are called parameters.Typical test parameters are the coupling or spacing between the test coil and the test object,test object electric conductivity,test object cracks,test object thickness,test object diameter,and test object magnetic permeability.

Small signal conditions are assumed so that changes in test parameters result in linear changes in test coil impedance or test coil output signals.We also assume that the test object is nonmagnetic so that the principle of superposition applies.The magnetic permeability of magnetic materials varies with magnetizing force.The nonlinear effect would cause cross modulation between the various signa

In the application of the multiparameter test,increased instrumen stability and accuracy are required as the number of parameters in the test is increased.The complexity of adjustment and the calibration of the equipment also increases as the number of parameters is increased.

A signal flow diagram,illustrating the different functions of the test appears in Fig.4.I.

Test coil assembly is driven by a multifrequency excitation signal $r_1(t)$.The term multifrequency is used to indicate that the signal has more than one frequency component,that in general it has many frequency components,or it has a broad spectrum.The multifrequency signals can be separated by using filters operating in the frequency domain.

The multifrequency function generator in Fig.4.I provides signals for excitation of the test coil assembly,which adjacent to or encircling the test object.All the excitation signals appear in the test coil simultaneously and induce currents within the test object at their respective frequencies.The test object parameters affect the flow of currents within the test object,thus modifying the electromagnetic field conditions both inside and outside of the test object.These effects modulate the test coil impedance and thus modulate the test coil output signals.The test coil assembly

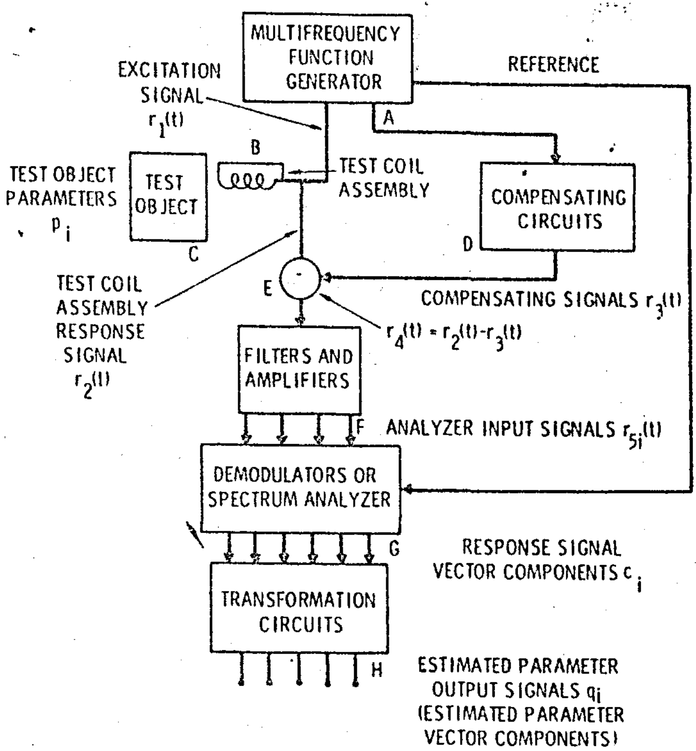


Fig.4.1 Multiparameter test method.Signal flow diagram.

response signal $r_2(t)$ carries in it modulation information concerning the test object.

The multifrequency function generator also provides excitation signals for the compensating circuits,which provide a compensating signal $r_3(t)$ which is subtracted from the test coil response signal at the summing point.The purpose of the compensating signal is to remove or subtract from the test coil response signal $r_2(t)$ a nominal fixed multifrequency signal $r_3(t)$ which reduces the dynamic range of the signal $r_4(t)$ applied to the filters and amplifiers.The compensating circuits,in many cases taking the form of bridge circuits,make it possible adjust the signal $r_4(t)$ to be a null signal for normal test object conditions.variations in test object parameters then cause this signal to differ from the null signal in accordance with the effects of the various parameters on the test coil output signal.

The compensating circuits are used to reduce the dynamic range of signals applied to amplifiers and detectors.This permits greater sensitivities with the resulting ability to detect the presence of small test object parameter variations.It should be emphasised that in theory a complete null is not necessary,but a good null prevents overdriving the amplifiers.

Next,the compensated signal $r_4(t)$ is applied to the filters and amplifiers.Here,in the multifrequency system,the signals are separated by means of wave filters having bandpass centered at the various excitation frequencies supplied by the multifrequency generator.The amplifier output signals (analyzer input signals $r_{5i}(t)$) are then supplied to the demodulators or spectrum analyzer.This analyzer produces the coefficients c_i of the orthogonal basis functions upon which the response signal is being expanded.In the case of multifrequency excitation,the expansion used is the sinusoidal Fourier series expansion where the basis functions are the sine and cosine fnctions associated with the various test frequencies.These C_i are the numbers represented in the circuit by signals.For a given test object parameters which are not varying with time,these coefficient signals likewise are fixed and do not vary with time. However,as the test object conditions change,the coefficient signals will change in accordance with the modulation of response signal as a result in the change of the test object parameters.The change in test object parametrs may be a result of the movement of the test object with respect to the test coil assembly or movement of the test object past a test coil assembly in a way that brings a change in test object parameters into the effective zone of the test coil. Amplitude-phase detectors perform a Fourier series expansion of signals, producing output signals of C_i.

The coefficient signals C_i next serve as input signals to the transformation circuits. These circuits operate upon the coefficient signals C_i, combining them in different proportions and polarities to provide output signals Q_i which are the estimates of the test object parameters P_i. The magnitudes of these components are read on meters.

A functional diagram is shown in Fig.4.2.

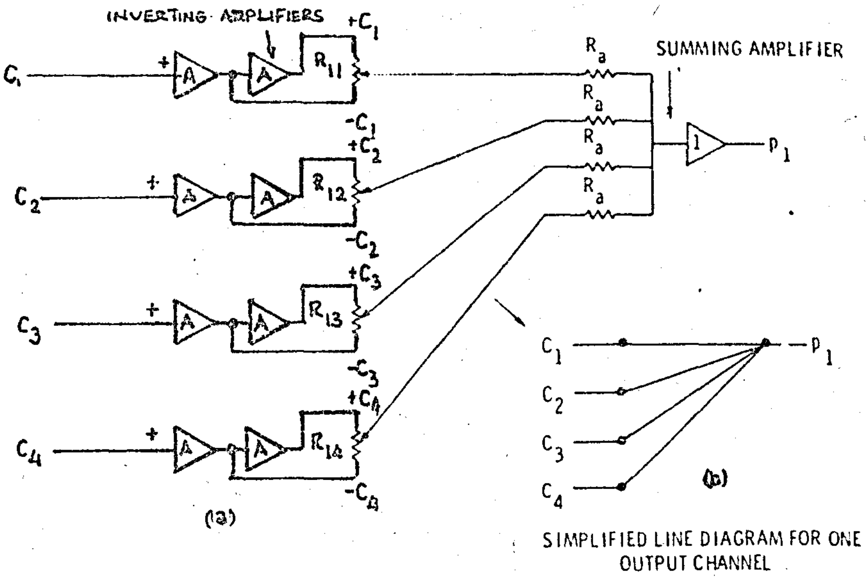


Fig.4.2 (a)Detailed circuit, one-channel output
(b)Simplified line diagram, one-channel output.

4.3 Four-parameter, Two-frequency Tube Tester

DESCRIPTION. A simplified block diagram of the device is shown in Fig.4.3. A 5 KHz and I5 KHz sinusoidal waveform generator provides excitation signals to bridge circuit and reference or switching signals to the two amplitude-phase detectors. The test coils are excited by the 5 KHz and I5 KHz excitation signals from the bridge circuit.The bridge circuit supplies null or near null test coil output signals to the two receiver channels comprising the 5 KHz amplifier and its associated amplitude-phase detector and the I5 KHz amplifier and its associated amplitude-phase detector.The outputs C_1,C_2,C_3,and C_4 represent the coefficients of the Fourier series expansion of the test coil-bridge output signal.In this particular test device the transformation circuits may be of a special type which provides for the succesive elimination of parameters.In other words,the effect of parameter variations on the signals in various portions of the transformation circuits can be eliminated one at a time.The principle of this transformation circuit will be discussed later.The advantage of the elimination of the parameter effects succesively is that it results in an easier experimental adjustment of the transformation circuits for the elimination of parameters with the general transformation circuit it is necessary that all the parameters that are required to be eliminated from a particular channel be varied in rapid succesion. In this way the several necessary adjustments of the different

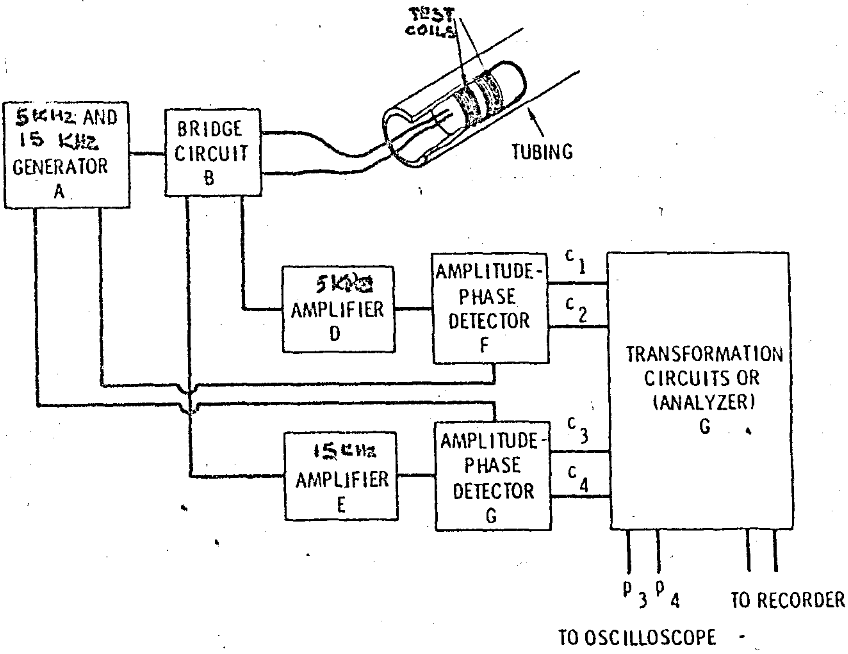


Fig.4.3 Four-parameter tubing tester (two frequency)

circuits can be made to meet the required settings for eliminating these parameter effects.Outputs of the transformation circuits are provided for both the oscilloscope and recorder.

SPECIALIZED TRANSFORMATION CIRCUIT:It is convenient to use simplified line diagrams when discussing transformation circuits.If the circuit components are shown in each diagram,the sense of signal flow is lost in the complexity of the amplifier and potentiometer connections.For example, Fig.4.2 illustrates the evaluation of simplified line diagrams for a general transformation circuit.First, in Fig.4.2a are shown the circuit components consisting of inverting amplifiers A,coefficient potentiometers R_{ij},summing resistors R_a, and summing amplifier I for producing the output signal for one channel.It is a function of this circuit to produce an output signal at point P_1,indicating parameter I output,which is a summation of the input signals C_i`s that are the coefficients of the Fourier series or generalized Fourier series expansion of the test coil output signals.To provide maximum flexibility,coefficient signals of both polarities must be provided for each input channel,along with the means to sum various proportions of these signals together to form the signal for one output channel.The inverting amplifiers A provide the positive and negative coefficient signals.The coefficient potentiometers R_{ij}`s provide for the selection of the different proportions of the coefficient signals.The four summing resistors R_a and summing amplifier I Serve to sum the outputs of the various coefficient potentiometers to provide the channel I output signal which will depend upon the variations in parameter I.

The portion of the transformation circuit just described is next shown in a simplified line diagram in Fig.4.2b.Although the inverting amplifiers,coefficient potentiometers,and summing circuit are not shown on the simplified line diagram,it is inferred that they are in fact present because their functions are required to give the desired output.

The next step in the evolution of the diagram is shown in Fig. 4.4,where the remaining three channels of a four, parameter general transformation circuit have been added.

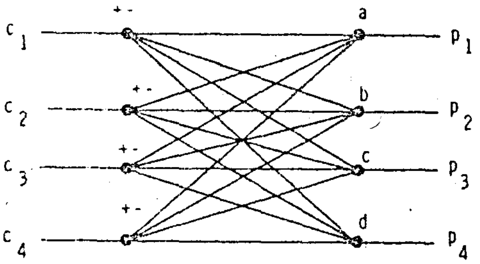


Fig.4.4 Four channel transformation circuit.(4-parameter)

Now that we have explained the simplified line diagrams for the transformation circuits,we can proceed with a description of the specialized transformation circuit used for the succesive elimination of parameters.The line diagram for this circuit is shown in Fig.4.5.Again,we have four input signals,the Fourier series coefficients C_1,C_2,C_3 and C_4.The signal functions existing within the transformation circuit after final parameter separating adjustments have been made are shown on each horizontal line of the diagram.The symbols shown on these lines indicate the parameters by

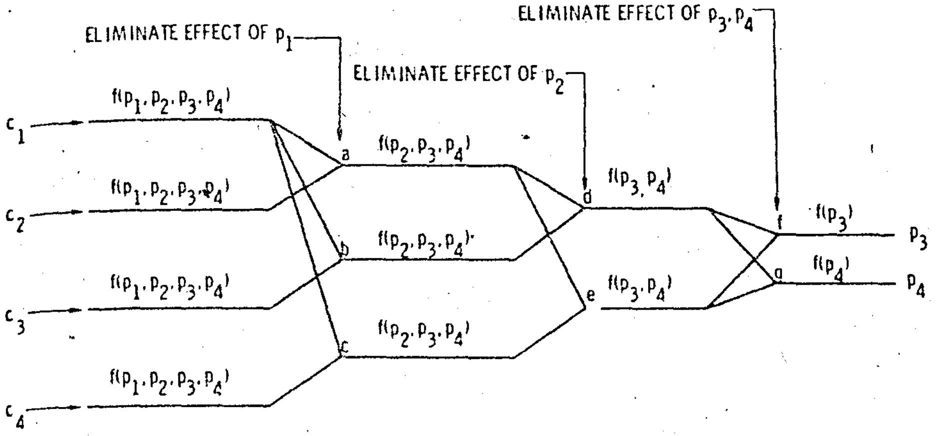


Fig.4.5 Transformation circuit for succesive elimination of parameters.

number which, in general, affect the signals on that particular line. For example, the expression $f(P_1P_2P_3P_4)$, indicates that all four parameters, in general, affect the values of input signals which are the Fourier coefficients. It will be noted that parameter P_1 is eliminated at the summing junctions a, b, and c. Thus the signals immediately following these summing junctions are a function of only P_2, P_3, and P_4. In a similar manner, parameter P_2 is eliminated at summing junctions d and e, producing signals which are a function only of parameters 3 and 4. Finally parameter 4 is eliminated at junction f, producing a signal at the P_3 output which is a function only of parameter 3, and similarly at summing point g parameter 3 is eliminated, leaving an output signal on channel P_4 which is only a function of parameter 4. The over-all effect of this circuit has been to eliminate the effects of parameters I and 2, producing outputs P_3 and P_4 which are affected by variations in parameters 3 and 4 respectively.

It will be noted that a major difference exists between these line diagram and the one in Fig. 4.4 for the general transformation circuit. The main difference is that in the succesive elimination of parameters, as accomplished by Fig. 4.5, one parameter at a time is eliminated. The operation of the circuit may be further clarified by considering the elimination of parameter 1 in detail. First, let us consider the elimination of the effects of parameter I at the output of the summing point a. The signals available at the coefficient potentiometers feeding this summing point are affected in general by all four parameters. As it is parameter I that we wish to eliminate at this summing point a, all we need to do is to cause the test object parameter I to vary, observe the summing point a, and adjust the coefficient potentiometers feeding summing point a so that the variation of parameter I has minimum or zero effect upon the output signal of the summing point a.Once this has been accomplished we move to the next summing point,summing point b, and repeat the same procedure.Next the effect of variation of parameter I at the output of summing point c is eliminated.This completes the elimination of the effect of parameter I on the output signals of summing points a,b,and c for a four-parameter problem.

Note that with this particular circuit only two parameters are read at the output,the other two having been eliminated.Additional read out channels for parameters I and 2 can be provided by the addition of more coefficient potentiometers and summing points for the elimination of parameters 3 and 4.The method just described is really the implementation of the method of Gauss for the succesive elimination of variables in a set of algebraic equations.Some interchange of input output signals C_1,C_2,C_3,and C_4 may be desirable for best results,as in the algebraic solution of equations by the Gauss method, (5).

CHAPTER-5

SENSING COILS AND THE FORMATION OF SIGNALS

5.1 Test-coil Arrangements

In most electromagnetic nondestructive tests the test coil serves as the main link between the test instrument and the test object. The test coil serves two main functions.The first of these is to establish a varying electromagnetic field which causes currents to flow in the adjacent or encircled test object or to cause ,in addition,magnetic effects in the magnetic domains of magnetic materials (if present).The second purpose is to sense the current flow and magnetic effects within the test object.

The over-all behaviour of test coil and electrical conductor systems is very complicated because of the wide variety of geometrical relations between the coils and the conducting test objects and the wide range of possible current flow paths within the test objects.In addition,many other complicating factors are present, with some of them not having compatible requirements.The test coil must be driven with excitation currents,and this requires the dissipation of some power within the test coil because of its I^2R losses.These losses can result in undesirable temperature increases in the test coil assembly,which can cause drift in instrument readings or may cause electrical noise.Similarly the currents flowing within the test object also causes power losses with an attendant increase in temperature,which can have an undesirable effect on electric conductivity determinations.

Although the same coil can be used for excitation and for supplying the response signal,this is not necessary and is often desirable. One coil can be used for excitation purposes with a second coil or multiple coils used for monitoring the electromagnetic field conditions.The use of separate excitation and sensing coils gives greater flexibility in meeting the test system requirements.For example, the primary electromagnetic field may be established by use of a few turns of relatively large wire driven from a low impedance generator,and the number of turns on the sensing coil can be adjusted to meet the input impedance requirements of the sensing circuits.If desired,sensing circuits having very high input impedance can be used,and the sensing coil may be wound with many turns of small wire.

The voltage output of a sensing winding is approximately proportional to the number of the winding when the excitation current and excitation winding turns are fixed.The word "approximately" is used here because it is not possible to place each turn of the sensing winding in a position so that it is threaded by the same flux which threads the other turns.This effect is important in the operation of the test coils.It is related to two other effects which are basic to the operation of test coils,and which we will call the "distance effect" and the "dipole effect".The distance effect is a direct result of the way in which an electron or group of electrons making up an elemental current affect the behaviour of other electrons.

The distance effect may be explained with the aid of Fig.5.I which shows an elemental current I $d\bar{l}_1$ flowing in a test object

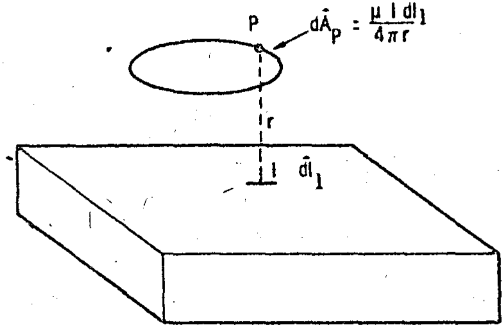


Fig.5.I Differential vector potential $d\bar{A}_p$ at a point P resulting from elemental current $Id\bar{l}_1$.

and a point outside of the test object at a distance r from the elemental current $Id\bar{l}_1$.Point P is also assumed to be located on a loop representing a single-turn coil around which we might sum elemental voltages to obtain the total induced loop voltage.The magnetic vector potential at point P resulting from the elemental current is

$$d\bar{A}=\frac{\mu Id\bar{l}}{4\pi r} \qquad (5.1)$$

where $\bar{A}$ is the magnetic vector potential,μ is the magnetic permeability of the medium,I is the current strength,$d\bar{l}$ is the vector current differential length,and r is the distance between the elemental current and the point at which the magnetic vector potential is to be evaluated.The electric field intensity at a point in free space is

$$\bar{E}=-\frac{d\bar{A}}{dt} \qquad (5.2)$$

where E is the electric field intensity and $\frac{d\bar{A}}{dt}$ is the time rate of change of magnetic vector potential.$\bar{A}$ is the total vector potential resulting from just one current element.In more realistic examples the total vector potential at a point is the result of the summation of the effects there which caused by all current elements in the system.The vector potential is directly proportional to the elemental current strength $d\bar{l}_1$ and inversely proportional to the distance r between the elemental current and the point at which the vector potential is being evaluated.Also of interest is the fact that the direction of this contribution to the magnetic vector potential is the same as that of the elemental current.Thus the distance effect operates in such a way that the induced voltage at point P,resulting from an elemental current,is inversely proportional to the distance between point P and the location of elemental current.

The induced voltage around a loop is equal to the summation of the elemental voltages induced in each section of the loop.This is summarised more precisely by the equation

$$V_i = \int \bar{E} . d\bar{l} \qquad (5.3)$$

where V_i is the total induced voltage around the loop and E is the electrical field intensity around the path of the loop.A very important factor enters here,resulting from the natural change in direction as the summation of elemental voltages $\bar{E}.d\bar{l}$ proceeds around the loop.The result of these in a specific case is shown in Fig.5.2,where we consider just the elemental induced voltages at two diametrically opposed points a and b of the loop.Points a and b are assumed to be equal distances from the current element $Id\bar{l}_1$.

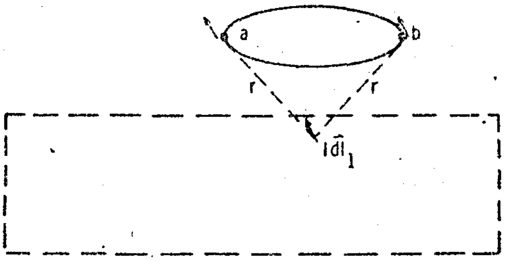


Fig.5.2 Cancellation of induced voltages in diametrically opposed sections of the loop under special conditions.

Both these two induced elemental voltages,or electric field strength vectors (one at point a and the other at point b),being caused by the same elemental current,have the same vector direction.However, it is apparent that when the summation of elemental induced voltages around the loop is made these two particular contributions will cancel.It is apparent also that some cancellation occurs owing to the natural circularity of the loop no matter what the location of the elemental current,with the cancellation becoming more complete as the two distances from the current element to two diametrically opposed points on the sensing loop approach equality. Thus,there are two main reasons why the sensitivity of the sensing loop to current flow within the test object falls off quite rapidly as the distance between the sensing loop and the test object is increased.First,we have the 1/r dependence of individual current element contributions to the vector potential at points around the loop,second,we have the cancellation effect resulting from the change in direction of the path of summation around the loop.The latter effect is called the dipole effect because at great distances from a current carrying loop the magnetic field approaches that which would be caused by two adjacent magnetic poles of opposite polarity located on the axis of the loop.

The inducting principles which we have been discussing in connection wfth the induction of voltage in the sensing loop as a result of current flow in the test object is also applicable to the induction of voltages or emf's within the test object caused by currents in the excitation loop or coil.This depicted in Fig.5.3,

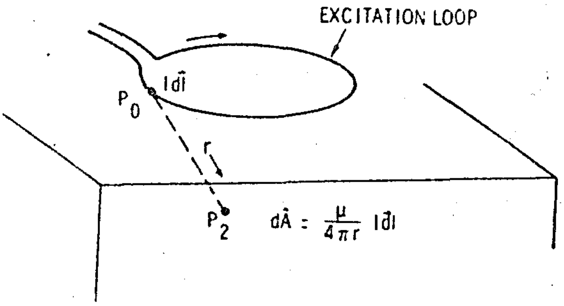


Fig.5.3 Induced voltage within a test object resulting from current element $Id\bar{l}$ in excitation loop.

where the current is now shown flowing in the excitation coil and the vector potential at point P_2 within the metal is shown.Here a current element $Id\bar{l}$ is assumed to flow in the excitation loop at point P_0,resulting in the magnetic vector potential $d\bar{A}$ at point P_2 in the metal.Again the distance r is the separation between the current element and the point at which the vector potential is being evaluated.

We can now consolidate Figs.5.2 and 5.3 to show a combined excitation loop and sensing loop to form a test coil assembly.This is shown in Fig.5.4,where the sensing loop is placed within the excitation loop.The sensing loop could as well be somewhat above, below,or outside the excitation loop,with some accompanying change in the operation characteristics of the assembly.We can now consider

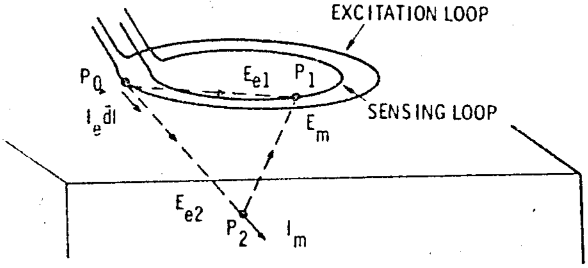


Fig.5.4 Combined excitation loop,sensing loop, and test object.

the individual effects of an elemental current $I_e d\bar{l}$ flowing within the excitation loop,at point P_2 within the test object and at point P_1 within the sensing loop.The current element $I_e d\bar{l}$ flowing within the excitation loop at point P_o causes an electric field intensity $\bar{E}_{e1}$ at point P_1 within the sensing coil and electric field intensity $\bar{E}_{e2}$ at point P_2 within the test object.This electric field intensity within the test object causes test object current I_m to flow at point P_2.This current in turn causes an electric field intensity $\bar{E}_m$ to exist at point P_1 within the sensing loop.Thus at point P_1,we have the summation of two electric field intensities,one resulting from the elemental excitation current and the other from the current which flows within the test object.Thus,the field intensity at point P_1 on the sensing loop resulting from current element $Id\bar{l}$ at point P_o on the excitation loop is

$$\bar{E}=\bar{E}_{e1}+\bar{E}_m$$

The total induced electric field intensity at a point,as at P_1, is the summation of the result of the effects of currents flowing everywhere in the whole system.Each point around the sensing loop receives contributions of electric field intensity from every elemental current,that is,every $Id\bar{l}$,around the excitation loop.The summation of $\bar{E}_e.d\bar{l}$ around the sensing loop is

$$V_i=\int_c \bar{E}_e.d\bar{l} \qquad (5.4)$$

where V_i is the total induced voltage around the loop resulting directly from the excitation current.

The effects of the presence of the test object are summed up in a somewhat similar but more complicated way.

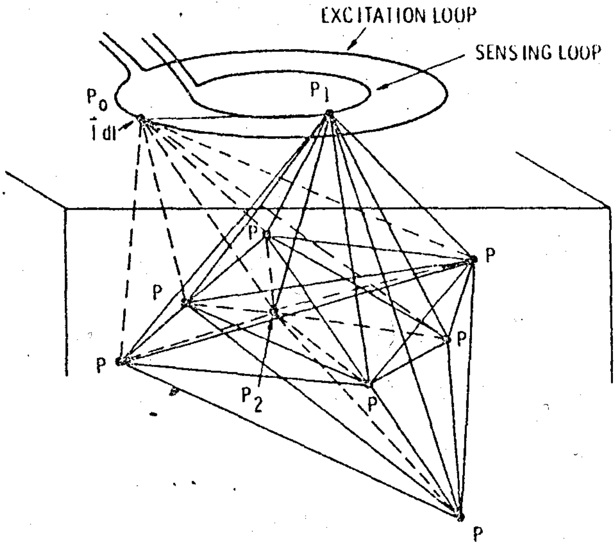


Fig.5.5 Final current flows in test object and induced voltages in sensing loop are a result of complicated interactions of all currents flowing

Fig.5.5 is an attempt to illustrate this rather complicated state.Point P_0 represents any point on the excitation loop,point P_1 represents any point on the sensing loop,and point P_2 represents any point within the test object.However,to aid in showing the complexity resulting from the interaction of currents at other parts of the test object,several other points in the test object are shown labelled P.Again,the new induced electric field intensity contributions at point P_1 on the excitation loop must be integrated around the loop along with the electric field intensity contributions from the current flowing in the excitation loop to give the total induced voltage of the sensing loop.

Three other effects,although basic but of lesser importance are : (a)the results of induced currents in the excitation and sensing winding themselves, (b)the effect of distributed capacitance of the loops or coils and their leads,and (c)the proximity effect which causes a redistribution of current flowing in the adjacent wires of the coils.

In all the discussions about the sensing loops and excitation loops it is assumed that the loops are nearly closed so that we can ignore the small space between the ends of the loop which are connected to the leads.It is also assumed that the leads are arranged so that no net voltage is induced in them.

The induced voltage of the whole multiturn is the summation of the induced voltages of each turn.Ofcourse,multiturn coils appear in many shapes and with many different spatial distributions of the turns.A statement that the output voltage of the whole coil is a simple summation of the individual turn voltages is an approximation.The distributed capacitance of the coil causes a shunt loading effect which actually results in current flow in the coil with accompanying voltage drops which change the coil output voltage. This effect increases as the frequency is increased.It is also larger for coils with many turns placed in close proximity.Eddy currents induced within the wire of the coil can also affect the output voltage.

ENCIRCLING COIL. Encircling test coils,having less resolution,have a higher test object output rate and require less complicated test object handling equipment.The encircling coils may be short or long,depending upon the application,(6)

The encircling coil is a very commonly used coil shaped for inspection of bars having circular cross-section and for the inspection of tubing and pipe.

Single, double, three-coil systems of alternative types can be designed for different purposes. Tangent coil, hybrid coil, through-transmission coil, rotating coil types are the other type of coils which are used for some other purposes, (7), (8).

5.2 Impedance of Test coils and the Formation of Signals

The impedance of the test coils does play a prime role in electromagnetic nondestructive tests. From the impedance point of view, it is the variation of the coil electric impedance which modulates the excitation current or excitation function, resulting in the varying test coil output signals. The variations in impedance are a result of the variations in current flow and magnetic field conditions within the test object. These current flow patterns and magnetic effects are themselves a direct result of the test object conditions.

The generation of the test coil output signal is depicted in Fig.5.7. A test object-test coil combination is shown in Fig.5.7a.

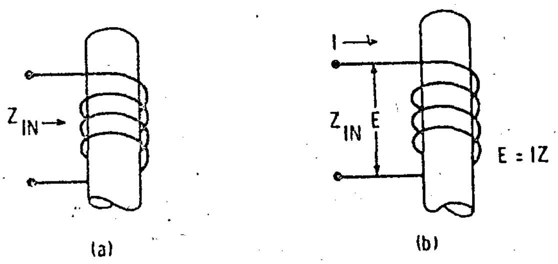


Fig.5.8 Test coil input functions: (a) test coil impedance (b) test coil voltage, constant current condition.

The test coil has electric input impedance Z_{in}. This input impedance is a function of frequency and of the test object conditions. The effects of the flow of currents within the test object and their mutual interactions are reflected in the coil impedance. Fig.5.7b shows a fixed ac excitation current I being applied to the coil. This applied current flowing in the test coil developes a voltage E across the impedance Z of the coil. Thus by application of Ohm's law we have

$$E = I.Z \qquad (5.5)$$

with fixed excitation current, the voltage developed across the coil is directly proportional to the impedance of the coil. If, instead of applying a fixed excitation current, a fixed voltage is applied to the coil, the ac current flowing in the test coil will vary with the impedance. The current, however, varies inversely with the impedance of the test coil, as can be seen by solwing Ohm's law for this case, giving

$$I = \frac{E}{Z} \qquad (5.6)$$

These two cases are extreme ones and actual operation generally falls somewhere between them. Thus, both coil current and coil voltag usually vary some with impedance changes of the coil.

FORMATION OF SIGNALS. The major portion of the formation of signals in the test coil occurs within the test coil-test object complex. However, there remains an important phase of the formation of the actual signals that are presented to the analyzing circuits of the receiver. The need for further modification of the test coil signals comes about because of limitations of the dynamic range of the amplifiers. The requirements of dynamic range can be reduced by subtracting from the test coil output signal a fixed component of the signal, leaving essentially only the portions of the signal which vary because of varying test object conditions. This is accom lished by use of bridge circuits or balance or null circuits, which effectively cancel the fixed portion (or a desired amount) of the fixed portion of the signal.

FORMATION OF SIGNALS BY SCANNING. Most electromagnetic nondestructive tests may be classified by either fixed tests or scanning tests In the fixed tests the test object is placed within or adjacent to the test coil assembly and the instrument output is read or recorded, this gives the information about the signal obtained for the test object in this fixed position relative to the test coil assembly.The signal during the placement is not used.The signal obtained is compared with the one obtained from a standard test object.Conductivity tests,some dimensional tests,tests for specific flaws in specific locations of a test part,and some localized thickness tests can be performed properly by fixed method of tests.

In the scanning tests a continuous signal is read while the test object is passed through or by the test coil assembly.Changes in continuously changing portion of the test object which is viewed by the test coil result in changes in the output signal or output signals.The waveform of the output signals depends upon the nature of the test object parameter variations,the relative velocity of the test coil and test object,and the extent and the shape of the sensitive zone of the test coil assembly.The instrument output is also a function of the electrical characteristics of the circuits used in the instrument,especially its frequency response characteristics,or,in other words,its passband.The scanning test is widely used for the inspection of wire and the other objects where long lengths or large surface areas are inspected.

Loci diagrams related to phase changes and amplitudes can be obtained.The signal loci caused by the presence of cracks and other test object irregularities can also result in curved signal loci.The curvature and relative phase angle of these signals carry information about the test object irregularities,(5).

5.3 Important Test Coil Parameters (or Characteristics)

Test coils are used to meet a wide variety of test conditions, and the relative importance of test coil characteristics varies according to the nature of the various tests.Important test coil parameters are resolution capability,size,electric impedance,electrical and thermal stability,sensitivity,power dissipating ability, low pressure and vibration sensitivity,resonant frequency,distributed capacitance,and coil configuration.

In many tests the sensitivity of the test coil assembly is of little concern because a lack of sensitivity may to a great extent be compensated by applying more power to the excitation of the test coil or by prowiding more amplification in the receiver.Many times,detection limits are set by unwanted signals caused by variations in the test object,which cause background signals that can not be eliminated by an increase in sensitivity.Test coil stability may be relatively unimportant in the scanning or ac differential tests,whereas it is usually very important in a fixed test or scanning test using absolute or dc output.

5.4 Test Coil Selection

The shape of the test object,the degree of resolution required, and the depth sensitivity requirements are important factors to be considered in the selection of test coils.A related test instrument design requirement and the selection of test frequency or test frequencies must be taken into consideration here.The skin depth varies inversely as the square root of the frequency,conductivity, and magnetic permeability.The type of test determines some of the test coil requirements.A fixed test requires good mechanical,electrical,and thermal stability of the test coil system,and the resolution requirements may or may not be important.In the scanning tests long-term stability may be less important than resolution and adaptibility for use with the mechanical scanning mechanisms. The function of temperature is less noticable in a scanning test where each section of a test object is exposed to the field of a coil for only a short time.Test coil assemblies usually have two final equilibrium temperatures;one without the test object in position and one with the test object in position.The thermal time constant may be longer than the desired inspection time to meet a required test rate.In this case the test coil temperature and test object temperature are continually varying.These effects can be reduced by use of low test coil excitation levels,(9).

CHAPTER-6

CIRCUIT DESIGN

6.1 Test Equipment Sections and Detailed Block Diagram

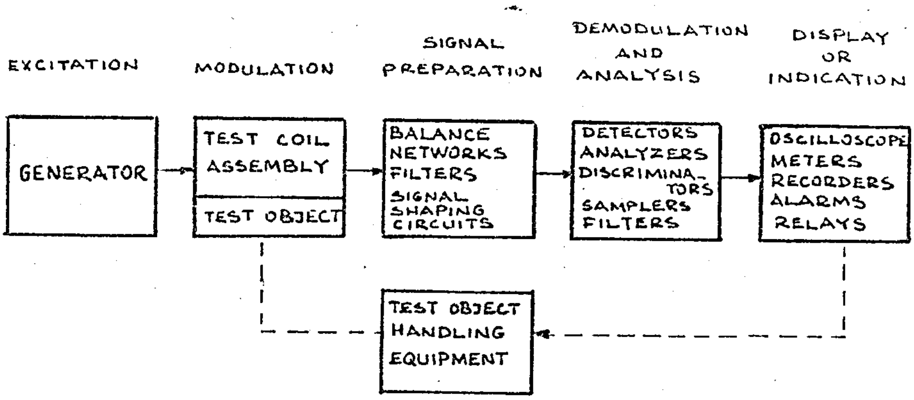


Fig.6.1 Internal functions of the electromagnetic nondestructive test.

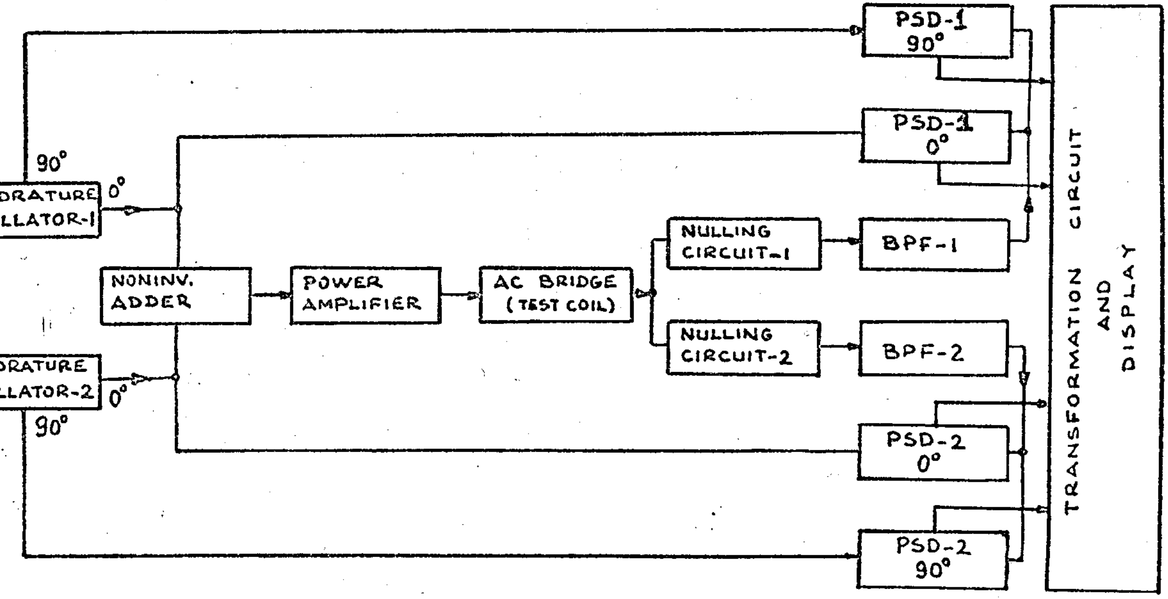


Fig.6.2 Detailed block diagram

6.2 Quadrature Oscillators

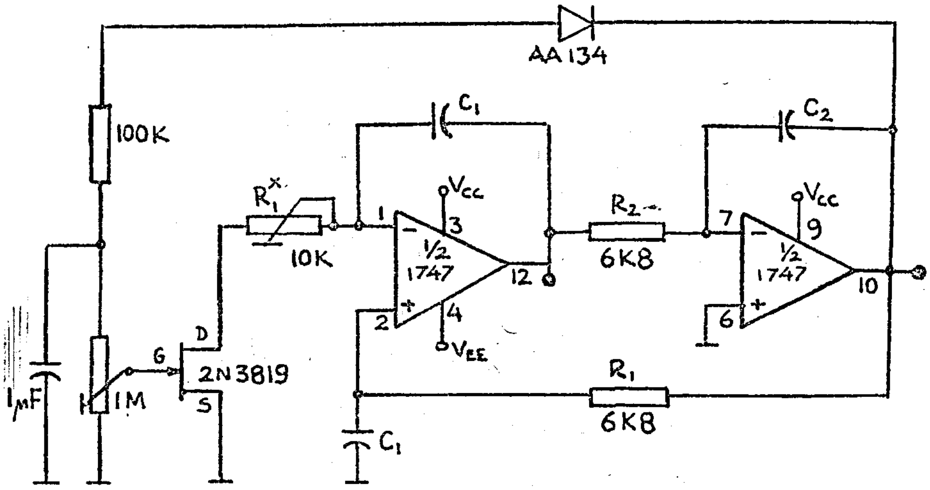


Fig.6.3 Quadrature oscillator

- Pin I2 : Sine output
- Pin 10 : Cosine output
- If $C_1=C_2=4.7$ nF : $f_o=4980$ Hz
- If $C_1=C_2=1.5$ nF : $f_o=15600$ Hz
- $R_1^x \leq R_1$
- $\omega_o=(R_1R_2C_1C_2)^{-1/2}$

6.3 Noninverting Adder

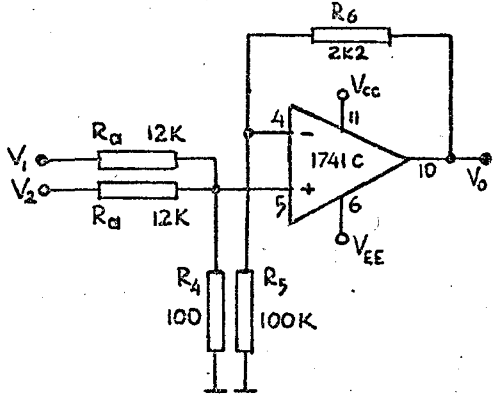


Fig.6.4 Noninverting adder

- $U=\frac{R_4}{R_a+R_4\cdot 2}(V_1+V_2)=\frac{R_5}{R_5+R_6}V_o$

- $V_o=\frac{R_5+R_6}{R_a+2R_4}\cdot\frac{R_4}{R_5}(V_1+V_2)$

- $V_{o,max}\cong 220$ mV is required since it is supplied to power amplifier which accepts that much of voltage at its input.

6.4 7W Power Amplifier

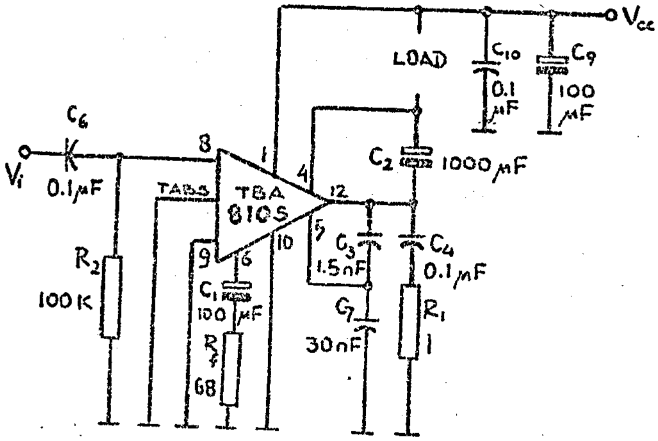


Fig.6.5 7W power amplifier

- Load is an ac bridge whose one arm is the "COIL"
- $V_{i,max} \cong 220$ mV

6.5 AC Bridge

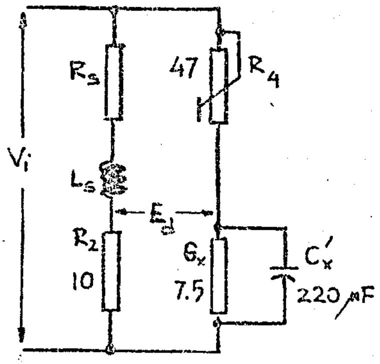


Fig.6.6 AC bridge

- $G_x = \frac{R_s}{R_2 R_4}$
- $C_x^1 = \frac{L_s}{R_2 R_4}$

6.6 Nulling Circuit

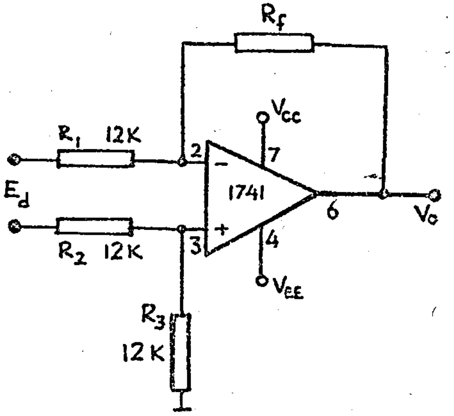


Fig.6.7 Nulling circuit

- To prevent saturation in BPF\`s,different outputs are provid
- For 4980 Hz BPF: R_f=12 K
- For 15600 Hz BPF: R_f=4K7

6.7 Band Pass Filters (BPF\`s)

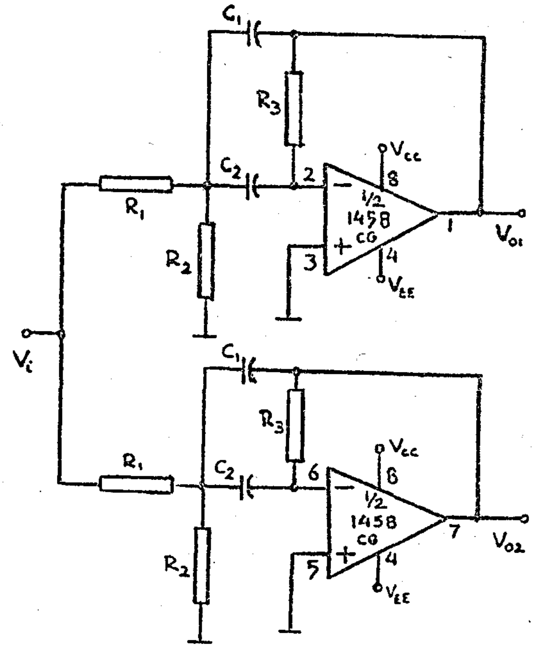


Fig.6.8 Band pass filters

- $BW=f_o/Q$, $R_1=Q/C_1\omega_o A_o$, $R^1 \; 1/\omega_o^2 R_3 C_1 C_2$, $R_2=R_1R^1/(R_1-R^1)$
- For f_o= 4980 Hz:

A_o=50 dB=316 , $Q=14>(A_o/2)^{1/2}$, BW=356 Hz , $C_1=C_2$=.47 nF , R_1=3 K , R_2=12K8 , R_3=1M9

- For 15600 Hz:

A_o=40 dB=100 , Q=14 > 7 , BW=1115 Hz , $C_1=C_2$=.47 nF ,

R_1=3 K , R_2=1045Ω , R_3=608 K

6.8 Phase Sensitive Detectors (PSD`s)

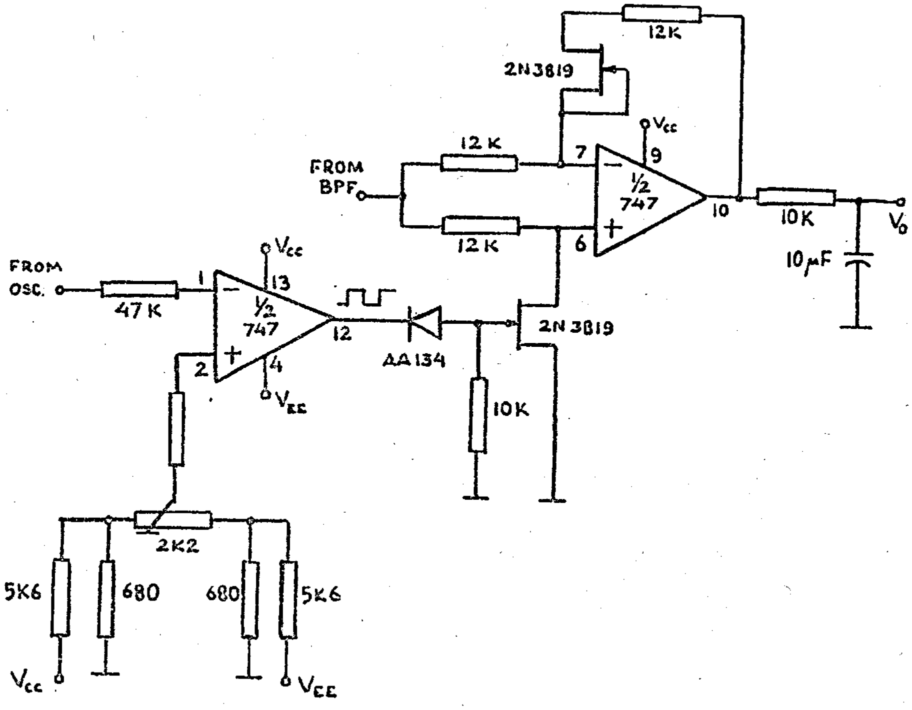


Fig.6.9 Phase sensitive detector circuit

6.9 Transformation Circuit

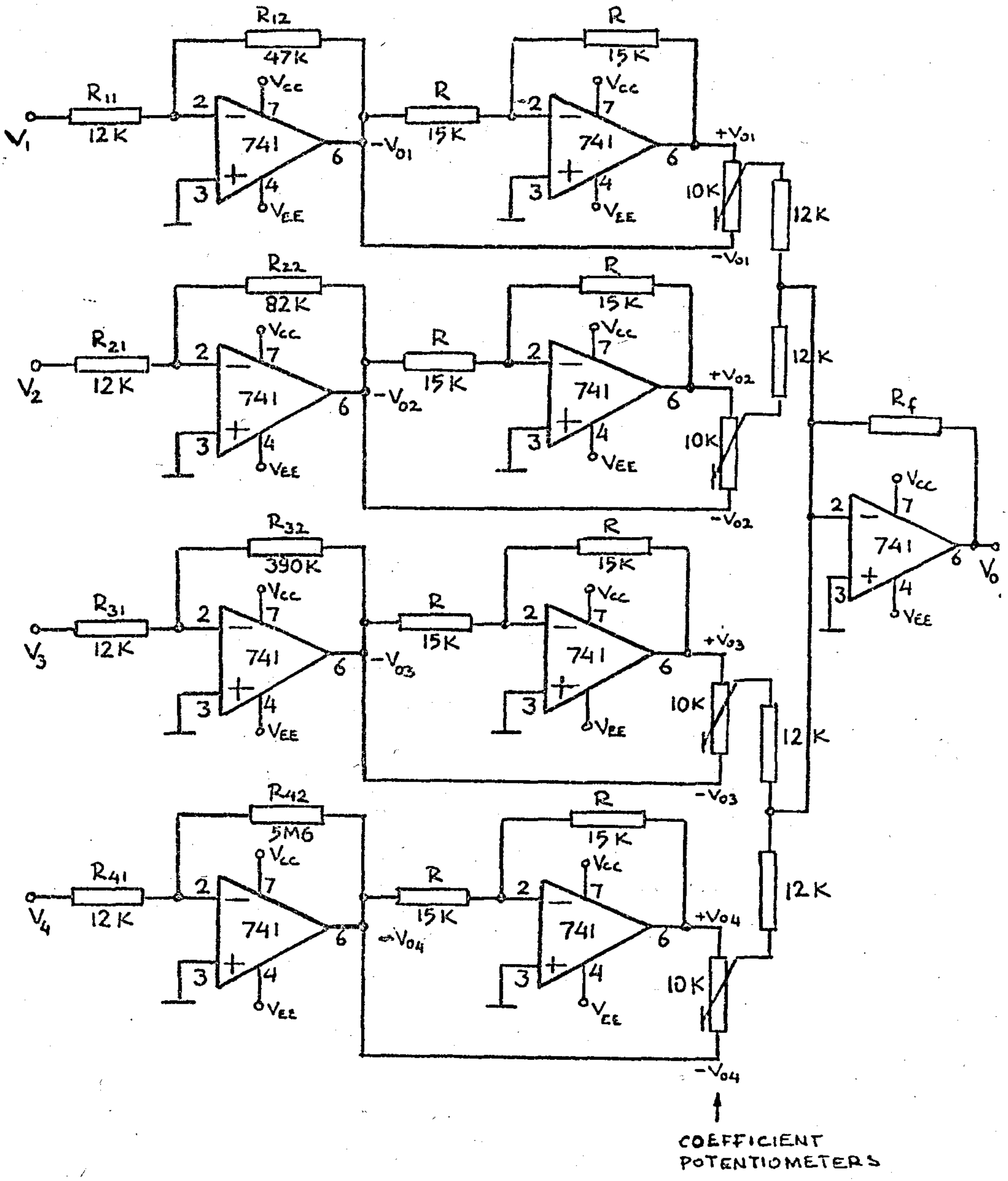


Fig.6.10 Transformation circuit

- $-V_{oi} = V_i \cdot R_{i2}/R_{i1}$

- R_{i2}\`s are determined according to the dc input levels in order to obtain compatible $-V_{oi}$\`s

- R_f is chosen either high or low, depending upon the desired output level and output sensitivity.

6.10 Display Circuit

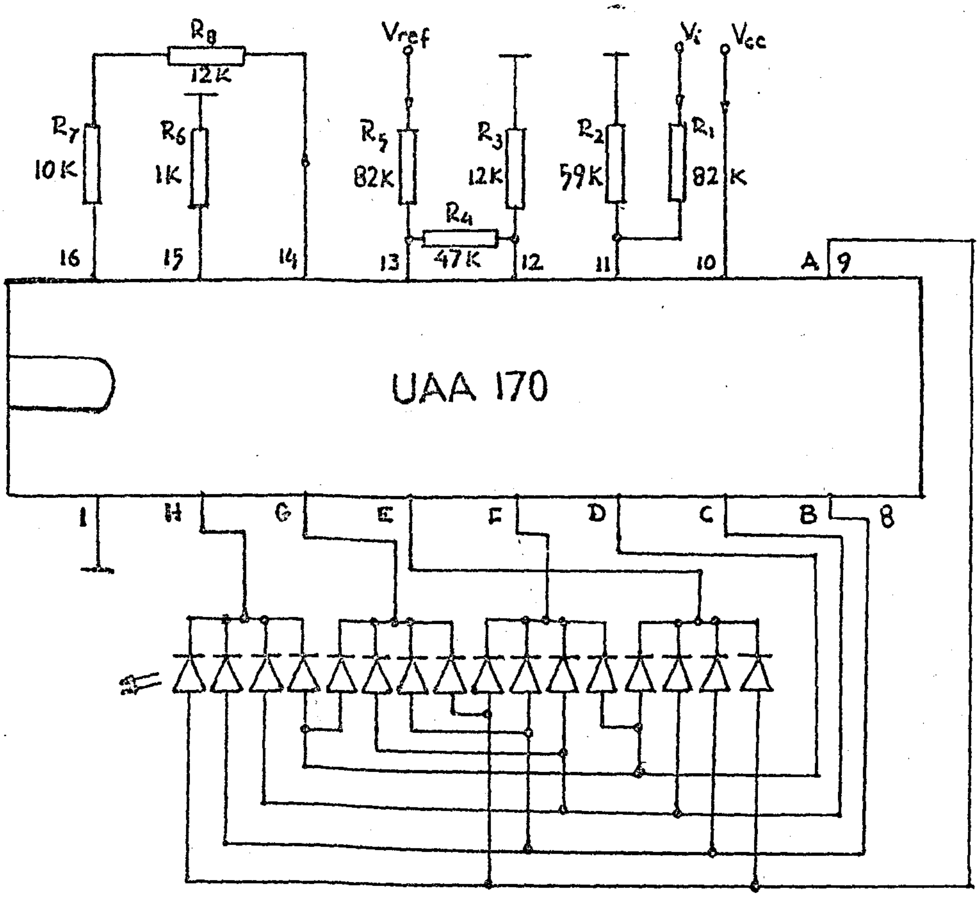


Fig.6.11 Display circuit

- $V_{ref}=V_{cc}=12$ V,dc
- V_i is provided by the transformation circuit.

6.11 Brief Descriptions of Some Circuits

QUADRATURE OSCILLATORS. The circuit shown in Fig.6.3 uses two operational amplifiers.In order to produce two sinusoidal signals with an exact phase difference of 90 degrees,they are connected in a feedback loop.The first amplifier is a noninverting integrator and the second one is an inverting integrator.The circuit can be considered as an analogue computing loop which is used for solving a differential equation of

$$\frac{d^2x}{dt^2}=-\omega^2x$$

The value of $x=a.\sin\omega t$ is a solution of that differential equation.The value of the angular frequency ω is determined by the time constants of the two integrators.

$$\omega^2=\omega_1.\omega_2 \quad \text{where } \omega_1=I/R_1C_1 \ , \ \omega_2=1/R_2C_2 \quad \text{then}$$

$$\omega=I/(R_1C_1R_2C_2)^{1/2} \qquad (6.I)$$

For oscillation condition,the resistor R_1^x must be slightly smaller than the resistor R_1.As the value of R_1^x gets smaller,the oscillation starts more rapidly but that causes a distortion in waveform.Using FET in series to R_1^x ,it will become easier to obtain rapid but less distorted waveform.

BPF.

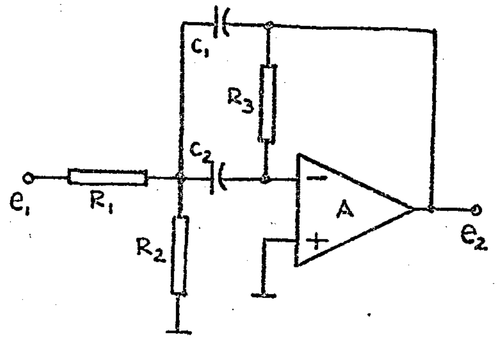


Fig.6.12 Basic network

When $R_2 \gg R_1$, R_2 is removed from the basic circuit.The maximum value of Q is approximately 20.As Q increases,R_2 decreases.Low R_2 attenuates the input signal.

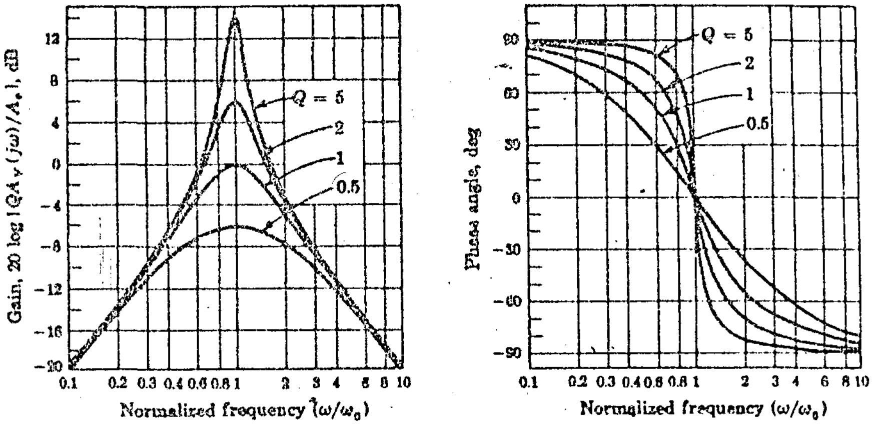
B ≡ -3 dB Bandwidth,Hz

f_o ≡ Center frequency,Hz

A_o ≡ Midband voltage gain,dB

$$H(s)=\frac{E_2(s)}{E_1(s)}=\frac{H\omega_o \cdot s}{s^2-\alpha\omega_o s-\omega_o^2} \qquad (6.2)$$

where $\omega_o=2\pi f_o$, $H=\alpha|A_o|$, $Q=f_o/B$



(a) (b)

Fig.6.13 (a) Gain, (b) Phase angle diagrams versus w/wo

$R_{eq}=\frac{R_1R_2}{R_1+R_2}$ and $Q>(|A_o|/2)^{1/2}$ relations must be satisfied for real components.

$$R_{eq}R_3C_1C_2=1/\omega_o^2 \qquad (6.3)$$

$$R_{eq}(C_1-C_2)=\frac{\alpha}{\omega_o}=\frac{1}{\omega_o\cdot Q} \qquad (6.4)$$

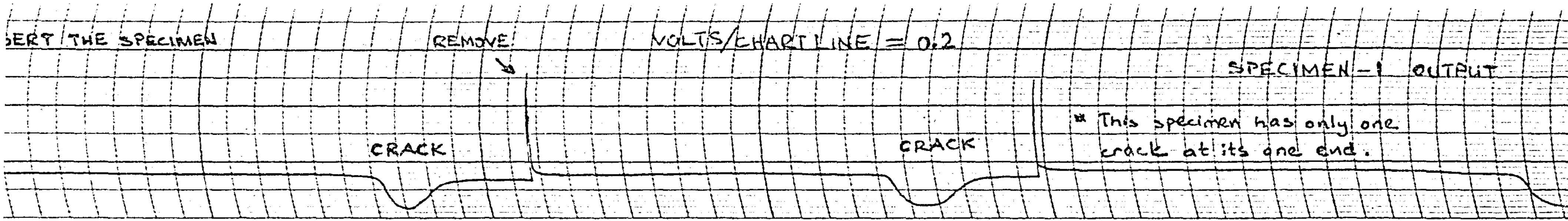
$$\frac{R_{eq}R_3C_2}{R_1}=\frac{H}{\omega_o}=\frac{A_o}{Q_o} \qquad (6.5)$$

Set $C_1=C_2$ and choose an appropriate C_1 that will yield R`s in the order of KΩ`s.

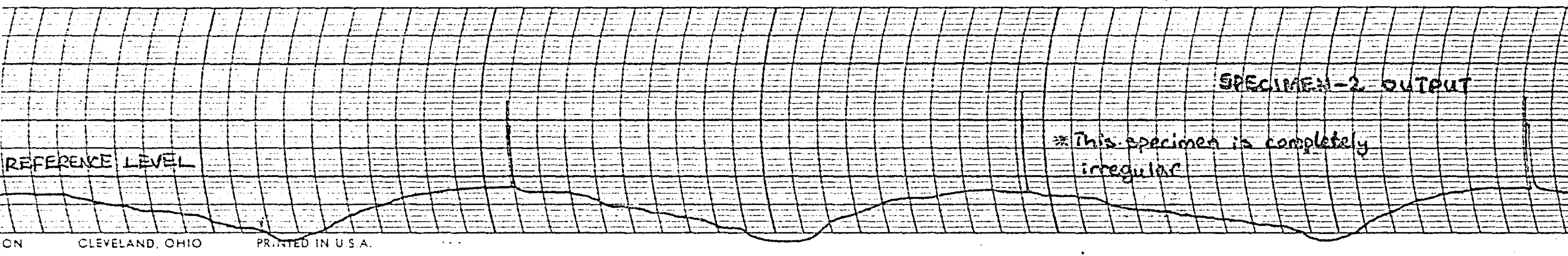
If $Q>(A_o/2)^{1/2}$ does not hold: Select R_1 and R_2 in KΩ`s. Then find C_1 and C_2. Selected R_1 should include the output resistance of the previous stage.

Find R_{eq} . $R_2\gg R_1$ allows to remove the resistor R_2. Then $R_{eq}=R_1$.

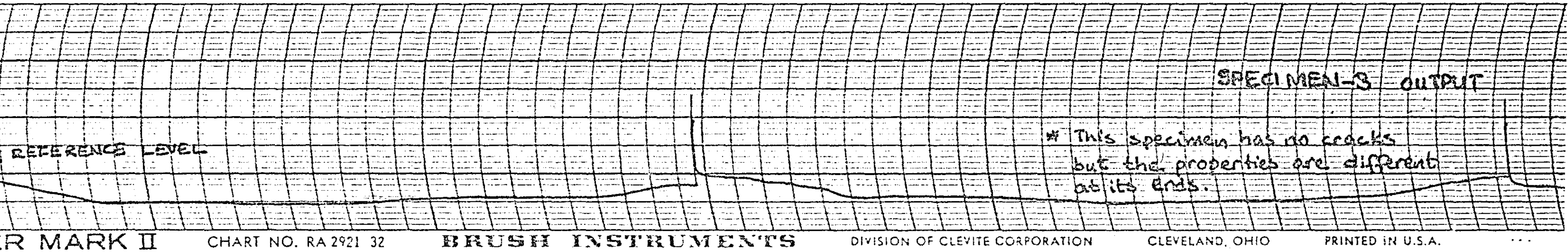
$$R_3=\frac{HQR_1}{1-\frac{QR_{eq}}{HR_1}} \qquad (6.6)$$



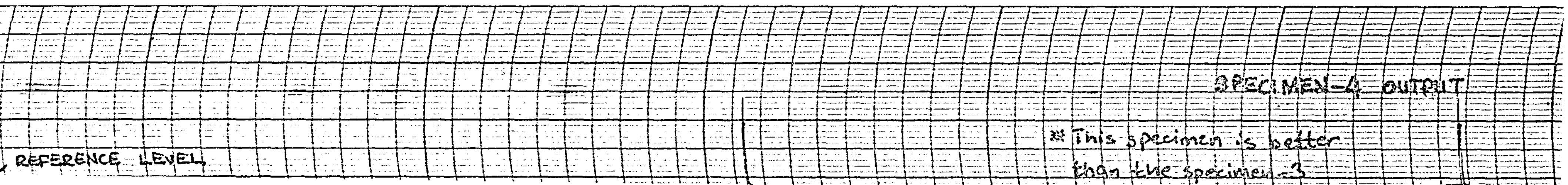
* This specimen has only one crack at its one end.



* This specimen is completely irregular



* This specimen has no cracks but the properties are different at its ends.



* This specimen is better than the specimen-3

$$C_2 = HR_1/R_{eq}R_3\omega_o \qquad (6.7)$$

$$C_1 = 1/HR_1\omega_o \qquad (6.8)$$

High Q is needed for minimum phase shift during the filtering. Thus the inequality for Q must be satisfied. If that inequality is satisfied, we may use the following useful equations for design.

$$R_1 = Q/C_1\omega_o A_o \qquad (6.9)$$

$$R_{eq} = 1/\omega_o^2 R_3 C_1 C_2 \qquad (6.10)$$

$$R_3 = Q(C_1+C_2)/\omega_o C_1 C_2 \qquad (6.11)$$

$$R_2 = R_1 R_{eq}/(R_1 - R_{eq}) \qquad (6.12)$$

PSD. Phase sensitive detector system yields dc outputs as responses to ac input signals. The input signal frequencies are equal to the reference signal frequencies. The obtained dc voltage from a PSD is proportional to the amplitude of the input signal and the cosine of its phase angle relative to that of the reference signal.

A PSD operates like a multiplier circuit which gives an output signal proportional to the product of the input signal and the reference signal. We consider a sinusoidal signal $e_s = E_s \operatorname{Sin}(\omega_s t + \phi)$ multiplied by a square wave reference signal. The square wave is assumed to be symmetrical about zero and to have unit amplitude.

For a square wave with unit amplitude it is possible to write

$$V_r = \frac{4}{\pi}(\operatorname{Sin}\omega_r t + \frac{1}{3}\operatorname{Sin} 3\omega_r t + \frac{1}{5}\operatorname{Sin} 5\,{}_r t) \qquad (6.13)$$

the product of these two signals will be

$$e_s \cdot V_r = \frac{4}{\pi}E_s(\operatorname{Sin}(\omega_s t - \phi)\operatorname{Sin}\omega_r t + \operatorname{Sin}(\omega_s t + \phi)\frac{1}{3}\operatorname{Sin}3\omega_r t + \ldots .)$$

$$= \frac{2}{\pi}E_s(\operatorname{Cos}((\omega_s - \omega_r)t + \phi) - \operatorname{Cos}((\omega_s + \omega_r)t + \phi) +$$

$$\frac{1}{3}\operatorname{Cos}((\omega_s - 3\omega_r)t + \phi) - \frac{1}{3}\operatorname{Cos}((\omega_s + 3\omega_r)t + \phi) + \ldots .) \qquad (6.14)$$

It is seen that at the input signal frequencies of $\omega_s=\omega_r; 3\omega_r; 5\omega_r;$ ...etc, the multiplied signals will give dc terms as $\frac{2}{\pi}E_s \cos\phi;$ $\frac{2}{\pi}E_s\frac{1}{3}\cos\phi;$ ...etc respectively.

After the multiplication process, a low pass filter is used in order to eliminate the ac parts of the product signal.

In Fig.6.9 the closed loop gain of the amplifier is switched between plus and minus unity by a square wave reference signal which is applied to the gate of the FET in the circuit. When FET is OFF the gain will be plus unity. (Because $I_i=I_f=0$ and $e_-=e_+=e_s$) When FET is ON (assuming $r_{DS}\rightarrow 0$; $e_o \simeq -e_s R_2/R_1 \simeq -e_s$) the gain will be minus unity. (T_2 is used for compensation of T_1). These processes illustrate the PSD's operation.

DISPLAY CIRCUIT. Input voltages beyond the selected indication range cause the diodes D_1 and/or D_{16} to light up so that only an exceeding of the range is recognized.

Provided that $R_2 = R_3 + R_4$ the following is valid.

$$\frac{V_{ref}}{V_{I2,I3}} = \frac{R_3+R_4+R_5}{R_4}$$

$$\frac{V_{ref}}{V_{i,min}} = \frac{R_3+R_4}{R_3}$$

$$V_{i,max} = V_{ref}$$

$$V_{cc,max} = 18\ \mathrm{V}$$

CHAPTER-7

COMPLEMENTARY DATA AND CONCLUSION

7.I Special Applications

(a)Detection of anisotropic conditions:Anisotropic conditions within a test object can be detected by using the directional properties of the magnetic fields of test coils.If the conductivity of the test specimen is different in two different directions, rotation of the test coil on the surface results in variation in test coil impedance,reflecting the effect of the anisotropy of conductivity.

(b)Inductive thermometry:Metal temperature can be monitored without contact with the surface.The effect that is monitored is the change in metal electric conductivity,resulting from changes in temperature.

(c)Eddy current sonic vibration test:An interesting combined eddy current and sonic test method for testing composite materials having one electrically conducting member has been described. Elastic vibrations are generated in the test part by forces developed between eddy currents flowing in metal sections of the test part are detected.Detection is performed by a sonic transducer receiving sonic energy radiated through the air from the test part. No coupling materials between the transducers and the test part are required.Undesirable test object conditions are detected by observing irregularities of the spectral response of vibrations compared with those of standard test objects.

(d)Eddy current ultrasonic transducer:An eddy current ultrasonic transducer generates and detects ultrasonic waves in nonferrous metals without use of any coupling medium except free space.

(e)Penetration depth:In nuclear reactors,the aluminum jackets of the nuclear elements are controlled by penetration test.

Additionally,eddy current flowmeter,coil temperature stabilization system,EM field mapping device,current flow observation in liquid metal,and many other special applications are possible by using the same principles.

7.2 Test Results

Crack detection,notch,dent and corrosion detections were achieved on different type of aluminum tubings.Faults were detected at the same locations on each experiment for the same tubing.The sensitivity of the test outputs can be increased or decreased easily by changing the feedback resistance value of the inverting adder amplifier which is fed by the coefficient potentiometers.At the same setting position of the coefficient potentiometers,large cracks give higher dc outputs than the smaller ones.The detection becomes difficult as the time proceeds due to the temperature effect of the test coil.For long-term measurements the coil design must be improved so that the temperature effect will decrease.

7.3 Device Operation

The use of the device produced for application purpose of the theory,is very simple.The coefficient potentiometers are adjusted freely to a reference point of light on the display system with a standard test object within the probe.Then the specimen which is to be used for testing is placed into the probe.Any change on the display during the scanning will mean that there exists a fault at that part of the test object.

7.4 Conclusion

In this study,aluminum tubings and rods are examined, however, by using the same principles, it is possible to make reliable tests on other nonferrous metals.

The most important considerations are the resolution and the test coil effects. Both of them are determined according to the type of applications. The test coil is a kind of transducer and should be optimized for each kind of operations.

Test coils can be produced in different sizes for different test object diameters and can be applied to the device directly by means of a socket.

For different types of materials, the frequency factor has a prime role. The starting point in frequency selection is the depth of penetration, which is affected by the conductivity and magnetic permeability of the material to be used. A variable frequency generator system will improve this study.

Multifrequency test method is an advanced method with respect to single frequency methods. Detecting and designating of faults are possible simultaneously with this method.

It is possible to find a wide application area to nondestructive eddy current test methods in industry. First of all, these methods are not time vasting and they are not laborious. Examination of regularly shaped products is easier than irregularly shaped ones. Nondestructive eddy current testing methods do not adversely affect the serviceability of the products.

APPENDIX-A

BASIC CONCEPTS

A.I Eddy Current

An electric current induced within the body of a conductor either moves through a nonuniform magnetic field or is in a region where there is a change in magnetic flux.It is sometimes called Foucault current.Although eddy currents can be induced in any electrical conductor,the effect is most pronounced in solid metallic conductors.Eddy currents are utilized in induction heating and to damp out oscillations in various devices.

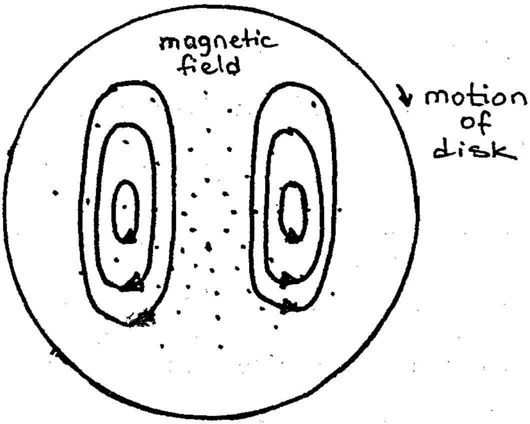


Fig.A.I Eddy currents which are induced in a disk moving through a nonuniform magnetic field.

CAUSES.If a solid conductor is moving through a nonuniform magnetic field,electromotive forces (emf`s) are set-up that are greater in that part of the conductor that is moving through the strong part of the field than in the part moving through the weaker part of the field.Therefore,at any one time in the motion there are many closed paths within the body of the conductor in which the net emf is not zero.There are thus induced circulatory currents that are called eddy currents.In accordance with Lenz`s Law,these eddy currents circulate in such a manner as to oppose the motion of the conductor through the magnetic field.The motion is damped by the opposing force. For example, if a sheet of aluminum is dropped between the poles of an electromagnet, it does not fall freely, but is retarded by the force due to the eddy currents set-up in the sheet. If an aluminum plate oscillates between the poles of the electromagnet it will be stopped quickly when the switch is closed and the field is set-up. The energy of motion of the aluminum plate is converted into heat energy in the plate.

Eddy currents are also set-up within the body of a material when it is in a region in which the magnetic flux is changing rapidly, as in the core of a transformer. As the alternating current changes rapidly, there is also an alternating flux that induces an emf in the secondary coil and at the same time induces emf`s in the iron core. The emf`s in the core cause eddy currents that are undesirable because of the heat developed in the core (which results in high energy loss) and because of an undesirable rise in temperature of the core. Another undesirable effect is the magnetic flux set-up by the eddy currents. This flux is always in such a direction as to oppose the change that caused it, and thus it produces a demagnetizing effect in the core. The flux never reaches as high a value in the core as it would if there were no eddy currents.

LAMINATIONS. Induced emf`s are always present in conductors that move in magnetic fields or are present in fields that are changing. However it is possible to reduce the eddy currents caused by these emf`s by laminating the conductor, that is, by building the conductor of many thin sheets that are insulated from each other rather than making it of a single solid piece. In an iron core the thin iron sheets are insulated by oxides on the surface or by thin coat of varnish. The laminations do not reduce the induced emf`s but if they are properly oriented to cut across the paths of the eddy currents,they confine the currents largely to single laminae,where the paths are long,making higher resistance;the resulting net emf in the possible closed path is small.Bundles of iron wires or powdered iron formed into a core by high pressure are also used to break up the current paths and reduce the eddy currents,(IO).

A.2 Electromotive Force (emf)

The electromotive force represented by the symbol around a closed path in an electric field is the work per unit charge required to carry a small positive charge around the path.It may also be defined as the line integral of the electric intensity around a closed path in the field.The term emf is applied to sources of electric energy such as batteries,generators,and inductors in which current is changing.

MAGNETIC FLUX.Lines used to represent the magnetic induction B in a magnetic field (magnetic induction = flux density)

$$\overline{B} = {}^{\overline{F}}/q\vec{v}\sin\theta = {}^{\overline{F}}/I\overline{l}\sin\theta \quad \overbrace{(Wb/m^2)}^{\text{tesla}} \text{ or } (N/A\text{-}m) \qquad (A.I)$$

$\overline{F}$:the force in a moving charge q

$\overline{l}$:length of current element

I:current

$\overline{v}\sin\theta$:the component of the velocity of the charge in a direction perpendicular to B.

A.3 Lenz`s Law

A law of electromagnetism which states that,whenever there is an induced emf in a conductor,it is always in such a direction that the current it would produce would oppose the change which causes the induced emf.If the change is the motion of a conductor through a magnetic field,the induced current must be in such a direction as to produce a force opposing the motion.If the change causing the emf is a change of flux threading a coil, the induced current must produce a flux in such a direction as to oppose the change.

Lenz`s law is a form of the law of conservation of energy, since it states that a change can not propagate itself.

APPENDIX-B

EM FIELD THEORY AND ELECTRIC CIRCUIT THEORY

B.I EM Field Theory

An electromagnetic field may be described by the vectors $\overline{E}$, $\overline{H}$,$\overline{D}$,and $\overline{B}$.The vectors E and H are the electric and magnetic field intensities,respectively.The vector $\overline{D}$ is the electric displacement or electric flux density,and the vector $\overline{B}$ is the magnetic induction or magnetic flux density.The electromagnetic field is a direct result of the presence of electric charge. Three states of electric charge result in different effects of interest.Stationary charges produce a static or stationary electric field.Charges moving at a uniform velocity produce in addition a magnetic field.Two major effects accompany a change in velocity of the charges.One is the change in the associated magnetic field which is accompanied by the production of an electric field.This produces a field in the vicinity of the moving charges (or electric current) which is called the induction field.The second major effect is the radiation of energy through the radiation field resulting from the acceleration of the electric charges.Thus,there are four interrelated field conditions.

I.Static electric field produced by stationary charges

2.Static magnetic field produced by charges moving at a constant velocity

3.Induction field produced by charges moving with varying velocity, producing interrelated varying electric and magnetic fields.

4.Radiation field produced by charges during periods of changing velocity.

Moving charges constitute an electric current flow,and the existence of flow leads to the concept of current density.The electric charge density is represented by ρ ,a scalar,and the current density,a vector quantity,is represented by $\overline{J}$.The current density $\overline{J}$ is related to the electric field intensity $\overline{E}$ by a form of Ohm’s law

$$\overline{J}=\sigma\overline{E} \qquad (B.I)$$

where σ is the electric conductivity of the material in which the current is flowing.

The vectors $\overline{D}$ and $\overline{E}$ are related by the electric permittivity ε and the vectors $\overline{B}$ and $\overline{H}$ by the magnetic permeability μ as follows:

$$\overline{D}=\varepsilon\overline{E} \qquad (B.2)$$

$$\overline{B}=\mu\overline{H} \qquad (B.3)$$

The vectors $\overline{E}$,$\overline{H}$,$\overline{B}$,$\overline{D}$ and $\overline{J}$ and scalar ρ are related by the Maxwell equations:

$$\overline{\nabla}\cdot\overline{D}=\rho \qquad (B.4)$$

$$\overline{\nabla}\cdot\overline{B}=0 \qquad (B.5)$$

$$\overline{\nabla}\times\overline{H}=\overline{J}+\frac{\partial\overline{D}}{\partial t} \qquad (B.6)$$

$$\overline{\nabla}\times\overline{E}=-\frac{\partial\overline{B}}{\partial t}=-\mu\frac{\partial\overline{H}}{\partial t} \qquad (B.7)$$

where in rectangular coordinates,

$$\overline{\nabla}=\text{del}=a_x\frac{\partial}{\partial x}+a_y\frac{\partial}{\partial y}+a_z\frac{\partial}{\partial z} \qquad (B.8)$$

$$\overline{\nabla}\cdot\overline{D}=\text{div}\,\overline{D}=\frac{\partial D_x}{\partial x}+\frac{\partial D_y}{\partial y}+\frac{\partial D_z}{\partial z} \qquad (B.9)$$

$$\overline{\nabla}\times\overline{E}=\text{curl}\,\overline{E}=a_x\left(\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z}\right)+$$

$$a_y\left(\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x}\right)+a_z\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right) \qquad (B.IO)$$

Maxwell’s equations give a complete description of the relation between the field quantities,charges,and currents.The total potential at a point is found by summing the scalar contributions of electric charges at different points to obtain the potential at one point.The electric field intensity at that point is then obtained by operating on the potential with $-\overline{\nabla}$.

In electrostatics, the potential V_r, at a distance r from charge q is

$$V_r = q/4\pi\varepsilon r \qquad \text{(B.II)}$$

The potential at a point resulting from charge distributed over a volume is

$$V = \int_v \frac{\rho dv}{4\pi\varepsilon r} \qquad \text{(B.I2)}$$

and the electric field intensity at the point is

$$\bar{E} = -\bar{\nabla} V \qquad \text{(B.I3)}$$

Another example is the use of a magnetic vector potential to aid in the solution of EM problems in a somewhat parallel way. A vector potential $\bar{A}$ is found such that the magnetic field vector $\bar{B}$ may be obtained directly by solving for the curl of $\bar{A}$:

$$\bar{B} = \bar{\nabla} \times \bar{A} \qquad \text{(B.I4)}$$

or

$$\bar{H} = \bar{\nabla} \times \bar{A} \qquad \text{(B.I5)}$$

Substituting (B.I5) into (B.5) and carrying out several intermediate vector algebraic operations results in the following equation relating the electrostatic potential V_r, the magnetic vector potential $\bar{A}$, and the electric field strength $\bar{E}$:

$$\bar{E} = -\bar{\nabla} V - \mu \frac{\partial \bar{A}}{\partial t} \qquad \text{(B.I6)}$$

where $V = \int_v \frac{\rho dv}{4\pi\varepsilon r}$

and

$$\bar{A} = \int_L \frac{\mu I d\bar{l}}{4\pi r} \qquad \text{(B.I7)}$$

or

$$\bar{A} = \int_v \frac{\mu \bar{J} dv}{4\pi r} \qquad \text{(B.I8)}$$

B.2 EM Field Theory and Electric Circuits

RESISTANCE ELEMENT. The resistors possess only conductance, the the capacitors possess only electric field effects, and the inductors have only magnetic fields or changing magnetic fields with the expected electric field effects.

First, applying Ohm's law to the resistor, we have

$$\bar{J} = \sigma \bar{E} \qquad \text{(B.I)}$$

where $\bar{J}$: current density, A/m^2

σ :conductivity,($\mho$/m) S

$\bar{E}$:electric field intensity,V/m

The internal voltage $V_{r,int}$ developed by the current flowing in the resistor is

$$V_{r,int} = -\bar{E}l = -l\bar{J}/\sigma \qquad (B.I9)$$

where l is the length of the resistor.

Now we multiply the numerator and denominator of the right-hand side of (B.I9) by the area A of the conductor to convert current density $\bar{J}$ to amperes.This results in

$$V = -\frac{l\bar{J}A}{\sigma A} = -\frac{lI}{\sigma A} \qquad (B.20)$$

where the coefficient $l/\sigma A$ is the resistance R.Thus

$$V_{r,int} = -RI$$

and the applied voltage V_{app} is

$$V_{app} = RI$$

CAPACITANCE ELEMENT.Maxwell's third law is

$$\bar{\nabla} x \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t}$$

Thus,we can write $\bar{\nabla} x \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} = \bar{J}_t$ (B.2I)

where $\bar{J}_t$ is the total current density,being the sum of the conduction current density $\bar{J}$ and the displacement current density $\frac{\partial \bar{D}}{\partial t}$.

We shall limit our region of interest to the space between two conductors (capacitor plates);thus $\bar{J}$ in (B.2I) is equal to zero. Since $\bar{J} + \frac{\partial \bar{D}}{\partial t}$ represents the total current density $\bar{J}_t$,and $\bar{D} = \varepsilon \bar{E}$,it follows that

$$\frac{\partial \bar{E}}{\partial t} = \frac{\bar{J}_t}{\varepsilon} \qquad (B.22)$$

and $d\bar{E} = J_t \cdot dt/\varepsilon$ or $\bar{E} = \frac{I}{\varepsilon}\int \bar{J}_t \, dt$. Converting $\bar{J}_t$ to current

$$\bar{E} = \frac{I}{\varepsilon A}\int \bar{J}_t A \, dt = \frac{I}{\varepsilon A}\int I \, dt \qquad (B.23)$$

converting E to internal voltage drop $V_{c,int}$ by multiplying by the distance between the plates gives

$$V=-\bar{E}l=-\frac{1}{\varepsilon A}\int I\,dt \qquad (B.24)$$

where $\varepsilon A/l$ is the capacitance of a parallel plate capacitor, neglecting end effects, where

A :area of capacitor plate, m^2

l :separation of plates, m

ε :permittivity of the space or the material between the plates: for free space $\varepsilon=\varepsilon_o=8.854\times10^{-12}$ F/m. The reciprocal of $l/\varepsilon A$ is the capacitance C, thus

$$V_{c,int}=-\frac{1}{C}\int I\,dt \qquad (B.25)$$

and $V_{app}=\frac{1}{C}\int I\,dt$

INDUCTANCE ELEMENT. The relationship between the current I and the voltage V of a coil can be obtained by using Faraday's law, which states that the induced voltage in a loop is proportional to the negative rate of change of flux which threads the loop.

$$V_i=-\frac{d\phi}{dt}=-\frac{d\int\bar{B}.d\bar{s}}{dt} \qquad (B.26)$$

where V_i :voltage induced in one turn

ϕ :total magnetic flux threading one turn

$\bar{B}$:magnetic flux density

$d\bar{s}$:elemental surface area of loop

When more than one turn is threaded by the same flux, the total coil voltage is

$$V_{ni}=-N\frac{d\phi}{dt}=-N\frac{d\int\bar{B}.d\bar{s}}{dt} \qquad (B.27)$$

where N is the number of turns.

The last two equations are also directly related to the Maxwell's equation of $\bar{\nabla}\times\bar{E}=-\frac{\partial\bar{B}}{\partial t}$ being integral form of it.

From Ampere's law

$$\int\bar{H}.d\bar{l}=I$$

which is an integral form of the Maxwell equation of

$$\bar{\nabla}\times\bar{H} = \bar{J} + \frac{\partial\bar{D}}{\partial t}$$

It is apparent that in general the magnetic field is proportional to the current. In the general case where turns of the coil are distributed in space, the contribution of the magnetic field at any point by the current flowing in the coil depends upon many factors. This applies also for the induced voltage. However, we can combine all these factors in one constant K_1 for a given coil and write V_{ni} as

$$V_{n,int} = -K_1 \frac{dI}{dt} \qquad (B.28)$$

The constant K_1 is called inductance L having the unit Henry, thus

$$V_{n,int} = -L \frac{dI}{dt} \qquad (B.29)$$

or

$$V_{app} = L \frac{dI}{dt} \qquad (B.30)$$

B.3 AC Quantities

PHASOR REPRESENTATION OF SINUSOIDS: A convenient way to represent sinusoids in equations and in graphics exists in which sinusoids of the same frequency are represented by complex numbers. The complex numbers represent both the amplitude and the phase of the sinusoid. The principle of the method can be explained by starting with a sinusoid to be represented. Let us assume that the sinusoid (Fig.B.I)

$$f(t) = A\ \mathrm{Sin}(\omega t + \theta) \qquad (B.3I)$$

(where A is the maximum value of the sinusoid) is to be represented. Euler's equation

$$e^{j\phi} = \mathrm{Cos}\phi + j\mathrm{Sin}\phi \qquad (B.32)$$

relates the exponential function $e^{j\phi}$ and the sine and cosine functions of ϕ (Fig.B.2). Multiplying both sides of Euler's equation by A gives

$$Ae^{j\phi} = A\ \mathrm{Cos}\phi + jA\ \mathrm{Sin}\phi \qquad (B.33)$$

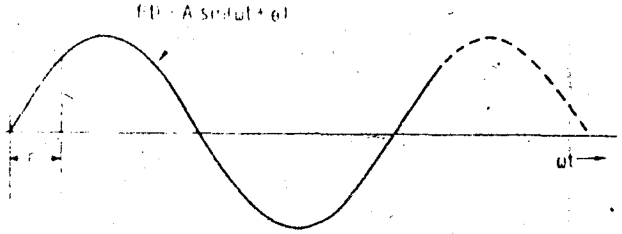


Fig.B.I Sinusoidal function

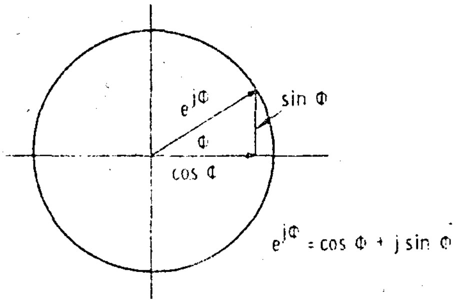


Fig.B.2 Euler's exponential equation relating the exponential and trigonometric functions

Substituting $\phi = \omega t - \theta$ in (B.33) gives

$$Ae^{j(\omega t+\theta)} = Ae^{j\theta}e^{j\omega t} = A\ \mathrm{Cos}(\omega t+\theta) + jA\ \mathrm{Sin}(\omega t-\theta) \qquad (B.34)$$

We now have a complex number $Ae^{j\theta}$ called a phasor on the left-hand side of the equation and the original function of time appearing along with other terms on the right-hand side of the equation.Equation (B.34) and the graphical construction in Fig.B.3 tells us the original function (A Sin($\omega t+\theta$)) can be represented by the complex number $Ae^{j\theta}$ if it is understood that to obtain

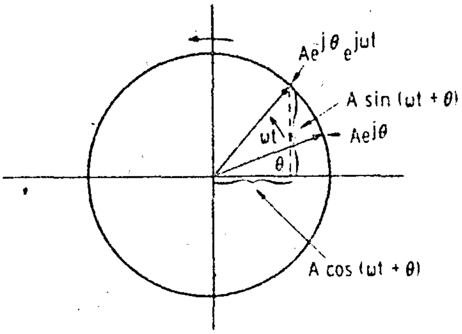


Fig.B.3 Phasor diagram

the original function $f(t) = A\ \mathrm{Sin}(\omega t + \theta)$ we

I.Multiply the phasor $Ae^{j\theta}$ by $e^{j\omega t}$, and

2.Use only the imaginary term, disregarding the factor j.

Actually, either the real or the imaginary component of $Ae^{j\theta}e^{j\omega t}$ can be used to represent the original function, but the phasors are different for the two cases. It is usual custom to use the real part of $Ae^{j\theta}e^{j\omega t}$ to represent the original sinusoid, probably because it is more satisfying to let "real" components represent "real" components.

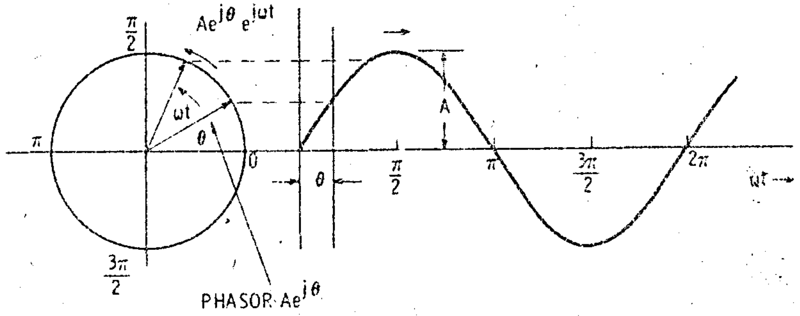
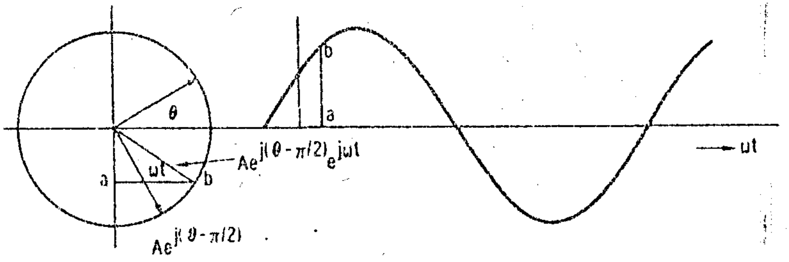


Fig.B.4 Relationship between the phasor and the sinusoid which it represents

Using the real part of $Ae^{j\theta}e^{j\omega t}$ to represent the original function f(t) would require that the angle θ in the phasor be replaced by $(\theta - \pi/2)$. This is shown in Fig.B.5



$\overline{ab} = \cos(\omega t + \theta - \pi/2) = \sin(\omega t + \theta)$

Fig.B.5 Alternative representation using the real part of $Ae^{j\theta}e^{j\omega t}$ to represent the function f(t)

NOMENCLATURE

emf	: Electromotive force	
EM	: Electromagnetic	
BPF	: Band pass filter	
PSD	: Phase sensitive detector	
$\bar{E}$	: Electric field intensity	V/m
$\bar{H}$	: Magnetic field intensity	A/m
$\bar{D}$	: Electric flux density	C/m^2
$\bar{B}$	: Magnetic flux density	(Wb/m^2), T
ρ	: Charge density	C/m^3
$\bar{J}$	: Current density	A/m^2
Q	: Electric charge	C
I	: Current	A
0	: Magnetic flux	Wb
V	: Electric potential	V
ε	: Electric permittivity	F/m
μ	: Magnetic permeability	H/m
R	: Resistance	Ω
C	: Capacitance	F
L	: Inductance	H
σ	: Conductivity	$(\mho/m)$, S
μ_0	: Permeability of free space	$8.854\text{x}10^{-12}$ F/m
ε_0	: Permittivity of free space	$4\ \text{x}10^{-7}$ H/m
c	: Velocity of EM propagation in free space $c = 1/\sqrt{\mu_0 \varepsilon_0}$	$2.998\text{x}10^{8}$ m/s

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