SYNCHRO
AND
RESOLVER
CONVERSION

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Synchro and Resolver Conversion

Handbook (Abridged Chapters 1 and 2 only)

ISBN 0-916550-06-0

Revision(s)

Revision	Description of Change	Editor	Date
A	Reformatted / Original Content – Appendices B, D, E N/A	AS	01/03/06

Synchro and Resolver Conversion

Handbook (Abridged Chapters 1 and 2 only)

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International Standard Book Number 0-916550-06-0

Published by Memory Devices Ltd, Central Avenue, East Molesey, Surrey, KT8 0SN. United Kingdom.
(Memory Devices Ltd is a division of Analog Devices Inc of Norwood, Mass. U.S.A.)

Phototypeset by Randall Typographic, 10 Barley Mow Passage, London W4 4PH.

Printed in Great Britain by Development Workshop Ltd.

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Foreword to 2nd edition

These reproduced chapters are as relevant today as they were when initially published 20 years ago. Almost every system has a rotating shaft somewhere in its mechanism. Because of this, measurement of shaft angles is one of the most prevalent requirements in system control today.

We therefore sought and gained permission from Ray Stata, co-founder and Chairman of Analog Devices, Inc., to reproduce this Synchro Handbook. Our aim in reproducing this is to promote a better understanding of the operation and use of synchros and resolvers. In turn, this knowledge will enable engineers around the world to benefit from the unique capabilities of this, as of yet, unsurpassed device.

In closing, I would like to thank the editor of this 2nd edition. Online access to this edition could not have been possible without the hard work and dedication of a man who had the foresight to understand the value of this handbook. Characteristically, this special individual saw the benefit and took the initiative to act.

Thank you John.

William Forman
CEO, North Atlantic Industries, Inc.
July 2001

Foreword to 1st edition.

This all started with the invention of the wheel....

Every industry is to some extent reliant on being able to measure angles, monitor rotation and control position, all of which involve transducing angular movement into electrical signals. Of the various transducers available for this purpose, the best, beyond question, are electromechanical synchros and resolvers. Industrial processes have over the past few years, become increasingly cost effective due to the availability of low cost digital computing, and consequently a need has arisen for converting the analog output of the synchro or resolver into digital information and vice versa. Our objective in writing this book has been to pass on to users information about synchro and resolver conversion, which may be of assistance to them in making their engineering decision

In writing the book we have tried to strike a balance between the heavily theoretical and the need for a primer. Inevitably we run the risk of being accused of "talking up" or "talking down" to our readers. We have run this risk deliberately in order to embrace the widest possible readership. Hopefully the virtuoso reader can always start with the appendices!

We trust that you will find this book useful and consider that we have achieved our objectives. We will welcome the comments and suggestions of our readers for the benefit of future editions.

VAL O'DONOGHUE
September 1980

Editors Note 2nd Edition

Synchros have played an important part in my business life since I first encountered the synchro as an element of Naval Gunnery control loops. This was during my service as an Instructor Lieutenant in the Royal Navy in 1958-61. I have since worked for all the major suppliers of synchro conversion electronics and it was during my time at Memory Devices Division of Analog Devices that the original Synchro and Resolver Conversion handbook was first written.

Geoff Boyes, who edited the first edition in 1980, makes the dedication to Dennis McDonnell who made an invaluable contribution but sadly died before its publication. Mac, as he was known, was the head of the Guidance Laboratory when I was working for him at Vickers Armstrong Guided Weapons Division, he was influential in my decision to join the Royal Navy .He thought that it sounded like a very good way to spend my National Service time, his words were, “at least when you come out you will really know Ohm’s law”, he was right, but I had also met the synchro which was to control the rest of my working life.

In editing this book it has been our intention to retain its considerable educational content but to remove references to actual products, we hope that by making the references generic in nature the book will not lose its value with time. In order to maintain relevance to the modern electronics some sections have been deleted and others modified.

For all these reasons I and the team have spent many hours scanning, editing both text and drawings and re-compiling this excellent Synchro Conversion Handbook, I hope all of you who read this book find it as enlightening as I have over the years.

John Gasking
North Atlantic Industries Inc October 2001.

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Chapter I -- Synchros and Resolvers

INTRODUCTION

Synchros and Resolvers have been available for about 40 years in various forms as part of electromechanical servo and shaft angle positioning systems. However only in the last decade has it been known that in conjunction with the appropriate interface electronics, the Synchro or Resolver can form the heart of a digital shaft angle measurement and positioning system, which in terms of reliability and cost effectiveness is unsurpassed by any other method. Although this publication is primarily concerned with examining in detail the methods and products available to perform this interface function, it is useful to look first at what Synchros and Resolvers are, how they compare with other angular transducers and what their traditional role has been since before World War II.

WHAT ARE SYNCHROS AND RESOLVERS?

Synchros

A Synchro is a generic term for a family of transducing instruments, the members of which can be connected together in various ways to form shaft angle measurement and positioning systems. All of these devices work on essentially the same principle which is that of a rotating transformer.

In appearance synchros are cylindrical and resemble small AC motors. They vary in diameter from 0.5 inches (12.7 mm) to 3.7 inches (94mm). On one end of the Synchro body is an insulated terminal block and on the other end is a flange enabling the synchro to be mounted by four screw clamps onto the mounting plate. Also at this end of the Synchro is the shaft which is normally threaded and splined. Synchro sizes are referred to by the outside diameter rounded up to the next largest number of tenths of an inch. Thus a Synchro with an outside diameter of 1.062 inches would be referred to as a size 11 while a Synchro with an outside diameter of 2.250 inches would be a size 23. A size 11 Synchro is shown in Fig. 1-1.

FIG. 1-1 A SIZE 11 SYNCHRO.
(Acknowledgements to Moore Reed and Co Ltd)

Internally almost all Synchros are similar in construction, having a rotor, with one or three windings (depending on the Synchro type) capable of revolving inside a fixed stator.

The rotor is an extension of the shaft. The three stator windings, which are connected in a star fashion 120 degrees apart, are brought directly to the terminals S1, S2 and S3 on the terminal block. The windings from the rotor are normally connected via slip rings and brushes to the terminals R1 and R2 (in the case of a single winding rotor). The internal structure of a Synchro control transmitter (which has a single rotor winding) and its electrical representation is shown in Fig. 1-2.

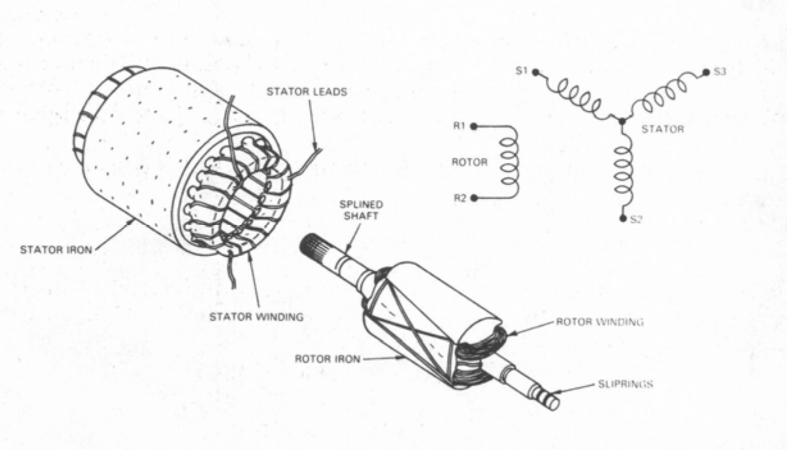


FIG. 1-2 INTERNAL STRUCTURE OF A SYNCHRO CONTROL TRANSMITTER and its electrical representation.

In general, if the rotor winding of a Synchro is excited by an AC voltage (called the reference voltage and normally at 60 Hz or 400 Hz), the voltage induced in any stator winding will be proportional to the cosine of the angle (θ) between the rotor coil axis and the stator coil axis. The voltage induced across any pair of stator terminals will be the sum or difference, depending on the phase, of the voltages across the two coils concerned.

For example, if the rotor of a synchro transmitter (which has a single rotor winding) is excited by applying across the terminals, R1 and R2, a reference voltage of the form:

$$A \text{ Sin } \omega t$$

The voltages which will appear across the stator terminals will be:

$$\text{S1 to S3} = A \sin \omega t \text{ Sin } \theta$$

$$\text{S3 to S2} = A \sin \omega t \text{ Sin } (\theta + 120^0)$$

$$\text{S2 to S1} = A \sin \omega t \text{ Sin } (\theta + 240^0)$$

where θ is the synchro shaft angle.

These voltages are known as synchro format voltages and will be referred to throughout this book. Synchros can be divided up into two types, Torque Synchros and Control Synchros.

Torque Synchros

These are required when it is necessary to transmit angular information from the shaft of one synchro to the shaft of another without the need for any form of servo system. The synchros themselves handle the necessary motive power.
The two most common Torque Synchros are:

Torque Transmitter (Symbol TX)

Torque Receiver (Symbol TR)

These two components are normally connected together as a `Torque Chain' as shown in Fig. 1-3.

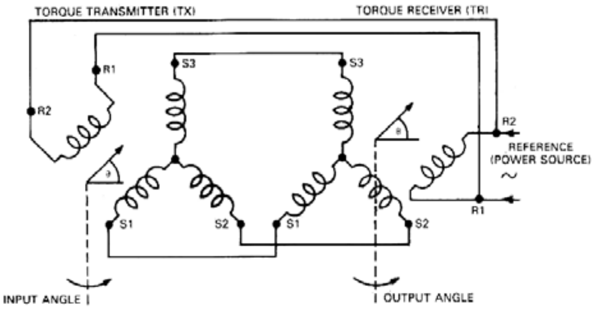


FIG. 1-3 A TORQUE RECEIVER AND A TORQUE TRANSMITTER connected as a torque chain.

In a Torque chain, the rotor of the Torque transmitter is excited with the reference voltage to produce the synchro format voltages on the SI, S2 and S3 stator terminals. Currents will then flow in the stator windings of both the Torque Transmitter and the Torque Receiver such that an alternating field will be set up in the stator of the Torque Receiver resembling that of the field in the stator of the Torque Transmitter. Rotating the shaft of the transmitter will therefore cause the shaft of the receiver to move in sympathy.

Torque chains such as this are accurate to ± 10 and are often encountered in systems where a rotating component is required to drive a remote pointer. Typical applications are in the transmission of data to instruments in ships and aircraft. The load which can be driven by the Torque Receiver shaft in a Torque Chain is limited, as there is no torque amplification.

In many instances today, existing Torque Chains such as this are being updated. In some cases the Torque Receiver is replaced by a Synchro to Digital converter and an L.E.D. display to give a digital readout of angular position. In other cases the Torque Transmitter is replaced by a Digital to Synchro converter so that an existing electromechanical pointer can be remotely driven from a digital input. These two types of modification are common where the existing Torque Transmitter and Receiver are to be found in separate equipment which are remote from each other and where only one equipment is being updated. One further member of the Torque Synchro family is worth mentioning.

Torque Differential Transmitter (Symbol TDX)

This device has two inputs, an electrical input, normally from a Torque Transmitter, and a mechanical input from the shaft. It gives out electrical synchro format signals, the power of which comes from the electrical synchro inputs (there is no reference input to a TDX). The output of the TDX is normally used to drive a Torque Receiver. The Torque Differential Transmitter has three windings on the rotor and three windings on the stator.

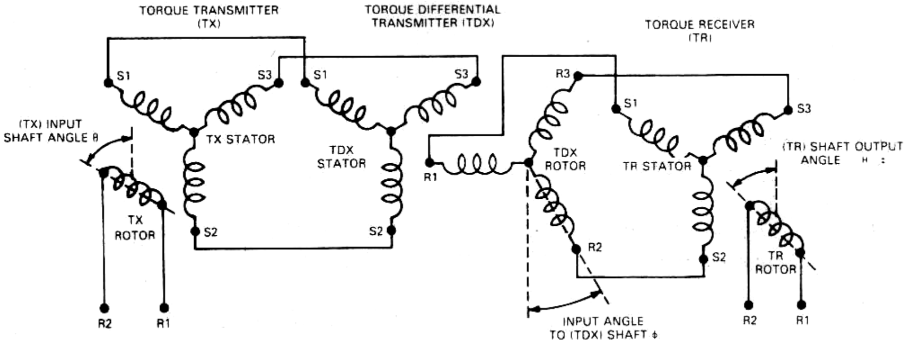


FIG. 1-4 A TORQUE CHAIN WITH A TORQUE DIFFERENTIAL TRANSMITTER (TDX)

The purpose of the TDX is to add or subtract the angle represented by the shaft from the angle represented by the electrical synchro format input, and to provide enough power to drive a Torque Receiver. A torque chain with a TDX included is shown in Fig. 1-4.Typical applications of the TDX will be found where it is necessary to introduce a variable angular offset into a Torque chain.

Control Synchros

As the name implies, these devices are used for providing and dealing with control signals in servo systems where accurate angular transmission to a mechanical load is required. It is important to remember that unlike the synchros of the Torque family, Control synchros are not required to handle any motive power for driving the load.

The two most common Control synchros are the

Control Transmitter (Symbol CX)
and Control Transformer (Symbol CT)

The Control Transmitter is really a high impedance version of the Torque Transmitter and is possibly the most common of all synchros.

If the rotor of a Control Transmitter (CX) is excited with the reference voltage:

$$A \sin \omega t$$

then the synchro format voltages will appear across the S1, S2 and S3 terminals. As these voltages are a function of the shaft angle 0, they will change when the shaft is rotated.Fig. 1-5 shows the voltages that would be expected on the terminals for two different shaft positions.

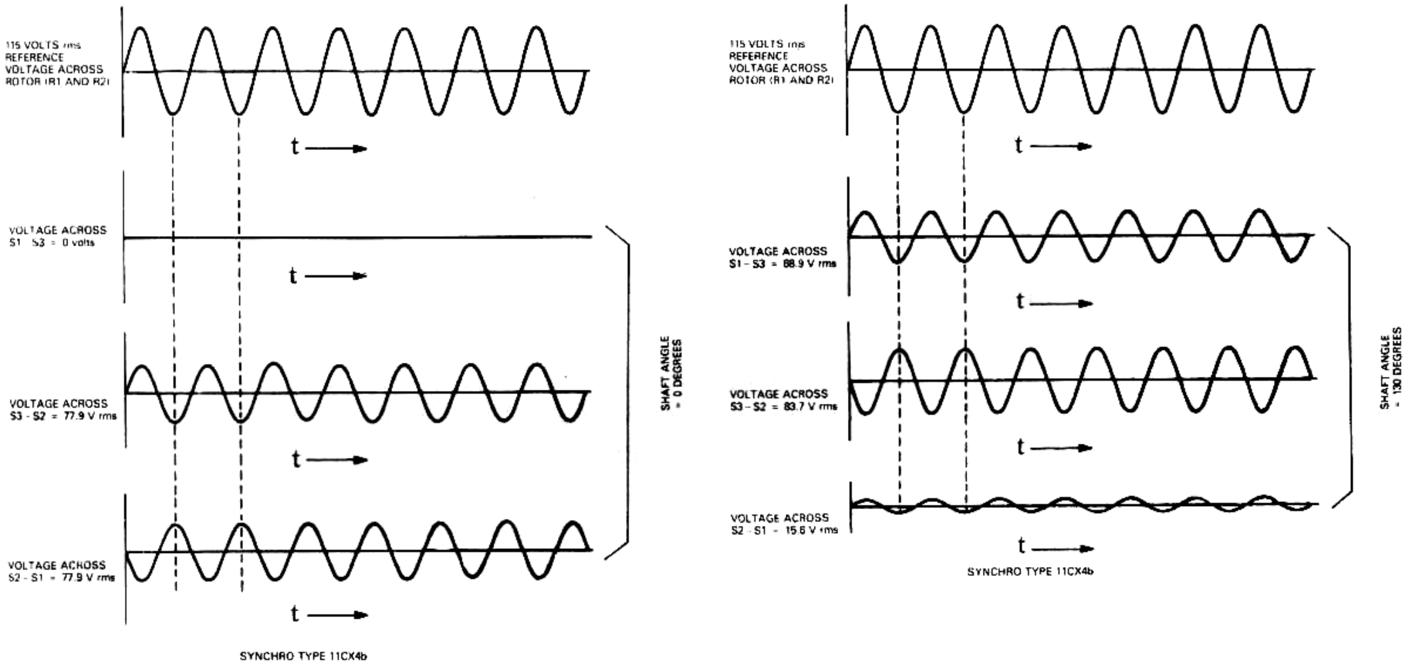


FIG. 1-5 CONTROL TRANSMITTER OUTPUT VOLTAGES FOR TWO SHAFT ANGLES.

Fig. 1-6 shows the waveform that would be generated across terminals 51 and S3 for continuous rotation of the shaft.

The output voltages from the CX are normally fed to a Control transformer (CT) to form a Control Chain. A Control Transformer is a high impedance version of the Torque Receiver with the rotor winding aligned at 90 degrees from that of a TR.

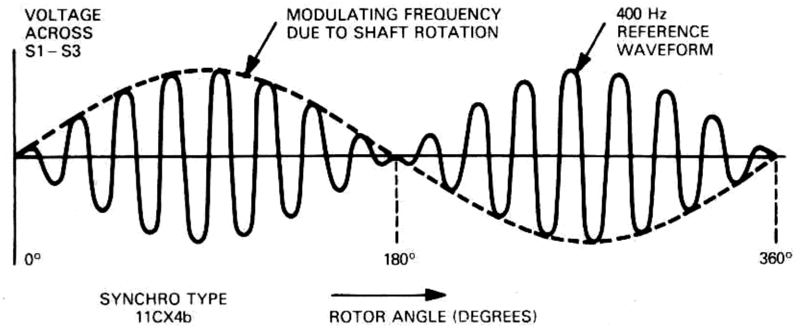


FIG 1-6 CONTROL TRANSMITTER OUTPUT VOLTAGE ACROSS S1 AND S3
For continuous shaft rotation.

A Control Chain is shown in Fig. 1-7.

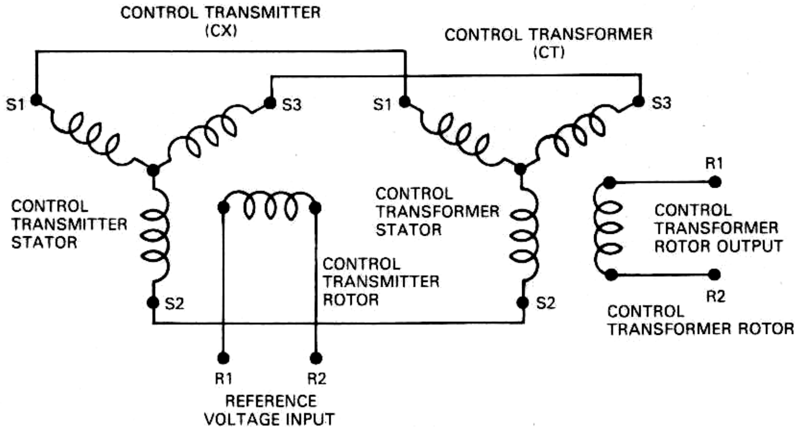


FIG. 1-7 A SYNCHRO CONTROL CHAIN.

In a Control Chain, when the shaft angle position of the C~ exactly equals the shaft angle position of the CT, a null voltage will appear on the rotor terminals RI and R2 of the CT. A slight deviation from this alignment will produce a signal in the rotor winding whose phase
relative to the reference voltage will depend on the direction of deviation. Fig. 1-8 shows the CT rotor output at and near alignment.

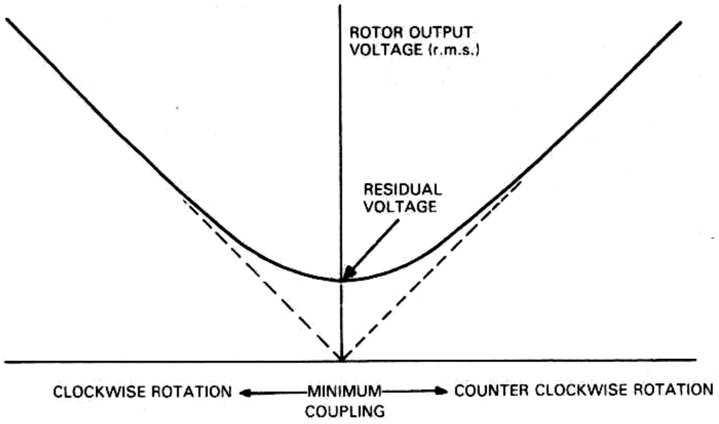


FIG. 1-8 CT OUTPUT FROM ROTOR AT AND NEAR ALIGNMENT.

The Control Transformer can therefore be considered as a null detector and is most often used as such in servo systems. In fact the null is never actually zero, there is always a residual voltage made up of three components namely, a fundamental voltage in phase with the normal (misaligned) output, a voltage of fundamental frequency but in quadrature to the normal output and a number of harmonics. Typical figures for a 115 v CT would be 30 mV for the Total Fundamental residual voltage and 60 mV for the Total Residual null including harmonics.

Fig. 1-9 shows a servo system using a control chain.

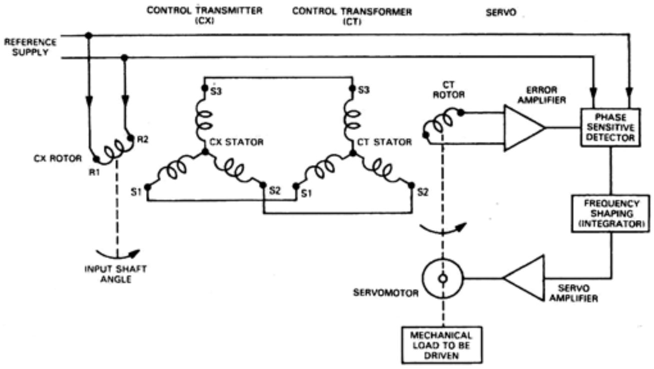


FIG. 1-9 A SERVO SYSTEM USING A SYNCHRO CONTROL CHAIN.

In Fig. 1-9, the servomotor, the CT shaft and the mechanical load to be driven (e.g. Gun mounting, compass repeater etc.) are all mechanically coupled together. When the shaft on the CX is turned to an angle θ, the outputs S1, S2 and S3 take up synchro format voltages defining angle θ, i.e.:

$$\text{S1 to S3} = A \sin \omega t \, \text{Sin} \, \theta$$

$$\text{S3 to S2} = A \, \text{Sin} \, \omega t \, \text{Sin} \, (\theta + 120^0)$$

$$\text{S2 to S1} = A \, \text{Sin} \, \omega t \, \text{Sin} \, (\theta + 240^0)$$

These voltages are coupled in the control chain to the CT stator windings via S1, S2 and S3.If we assume that the CT is not at angle θ, then a voltage will be produced on the CT rotor windings. This will be fed into a high impedance amplifier and phase sensitive detector to produce an error signal. This error signal is amplified by a servo amplifier which causes the servomotor to drive the load and the CT shaft to the position where the CT rotor voltage is at a minimum. This position will be angle θ. The direction which the motor chooses to drive towards angle θ is determined by the phase of the rotor signal with respect to the reference voltage.

In many applications and in particular during the update of existing equipment, it is required to drive a servo of this type from a digital input. In such cases, the CX can be replaced by a Digital to Synchro converter (which in effect is a solid state CX) and the demand angle fed into the system digitally. This is illustrated in Fig. 1-10.

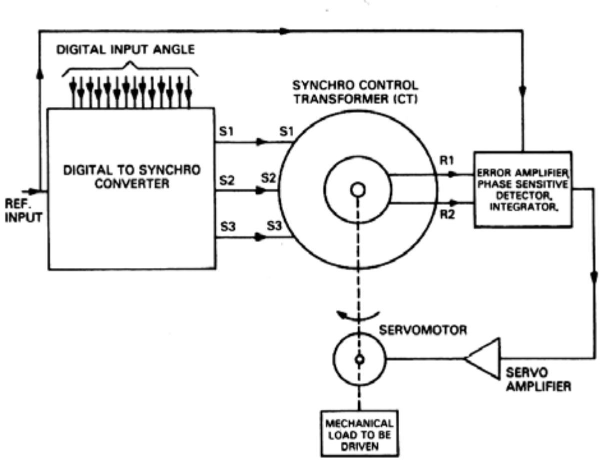


FIG. 1-10 THE USE OF A DIGITAL TO SYNCHRO CONVERTER
to drive a servo System

The other member of the control synchro family is the Control Differential Transmitter (Symbol CDX)

This is the control synchro equivalent of the Torque Differential Transmitter previously described, and is used to add or subtract a mechanical shaft angle into the control chain. Before describing how Resolvers differ from Synchros, it is worth mentioning that most synchros fall into one of three voltage and reference frequency categories, viz.

(1) 60 Hz reference frequency with a 115 volt r.m.s. reference and a 90 volt r.m.s. line to line signal voltage.
(2) 400 Hz reference frequency with a 115 volt r.m.s. reference and a 90 volt line to line signal voltage.
(3) 400 Hz reference frequency with 26 volts r.m.s. reference and an 11.8 volt r.m.s. line to line signal voltage.

Resolvers

The Resolver is a form of synchro (Resolvers are very often called Synchro Resolvers) in which the windings on the stator and rotor are displaced mechanically at 90^0 to each other instead of 120^0 as in the case of synchros. The Resolver therefore exploits the sinusoidal relationship between the shaft angle and the output voltage.

In outward appearance, Resolvers are very similar to Synchros and are produced in the standard Synchro frame diameters. Internally, Resolvers come in many forms with a wide variety of winding configurations and transformation ratios. The simplest Resolver would have a rotor with a single winding and a stator with 2 windings at 90^0 to each other. It would be represented as shown in Fig. 1-11.

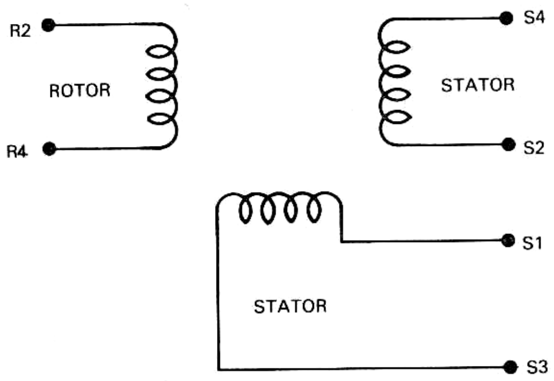


FIG. 1-11 ELECTRICAL REPRESENTATION OF A SIMPLE RESOLVER

If we assume that the rotor is excited by an AC reference voltage:

$$A.\mathrm{Sin}\ \omega\ t$$

Then the voltages appearing on the stator terminals will be:

$$\text{S1 to S3} = V.\mathrm{Sin}\ \omega\ t.\mathrm{Sin}\ \theta$$
$$\text{and S4 to S2} = V.\mathrm{Sin}\ \omega\ t\ \mathrm{Cos}\ \theta$$

where θ is the Resolver shaft angle.
These voltages are known as Resolver format voltages arid will be referred to extensively during the rest of this book. Such a Resolver could be used simply as an angular transducer in much the same way as a synchro transmitter. A more complex Resolver would have two rotor windings at 90^0 to each other and two stator windings also at 90^0 to each other. This would be represented as shown in Fig. 1-12.

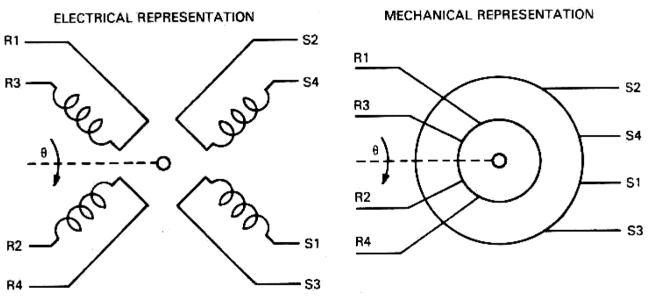


FIG. 1-12 REPRESENTATION OF A RESOLVER WITH TWO ROTOR WINDINGS

This Resolver type can be used as an angular transducer in one of two ways. If one of the rotor windings is short circuited and the other rotor winding is excited with the reference voltage, A Sin w t, then the Resolver Form outputs will be available on the Stator terminals S1, S2, S3 and S4. Alternatively, and more usually, one of the stator windings is short circuited and the other winding excited with the reference voltage, causing the Resolver Format signals to be present on the rotor winding terminals R1, R2, R3 and R4. Resolvers used for angular measurement as described above are known as Data Transmission Resolvers, and a control chain can be set up using:

	a Resolver Transmitter	(Symbol TX)
and	a Resolver Control Transformer	(Symbol RC)

These control chains are analogous to the Synchro control chains described earlier. Such a control chain is shown in Fig. 1-13.

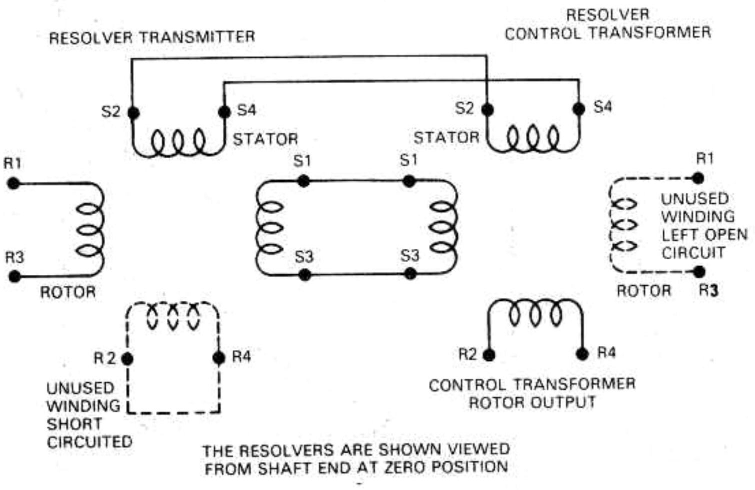


FIG. 1-13 A RESOLVER CONTROL CHAIN

Resolvers are not available as Torque components.

Another application of Resolvers is in a computing mode, and when used for this purpose, they are known as Computing Resolvers. For example, a Computing Resolver has two stator windings and two rotor windings and can be used to perform a polar to rectangular or Cartesian Co-ordinate conversion.

e.g. Assume that the polar co-ordinates of a point are represented by a voltage E Sin ωt and an angle θ. If θ is the angle applied to the Resolver shaft and is E.Sin ω t applied to one of the stator windings as the reference voltage V5 ~ (the other stator winding being short circuited), then the Resolver Format voltages appearing on the rotor will be:

$$V_{R1-R3} = E.\mathrm{Sin}\ \omega t\ .\mathrm{Sin}\ \theta.$$

and $$V_{R4-R2} = E.\mathrm{Sin}\ \omega t\ .\mathrm{Cos}\ \theta.$$

These voltages will represent the Cartesian or Rectangular coordinates of the point.

Fig. 1-14 shows an example of a Polar to Cartesian coordinate conversion used in a height finding radar.

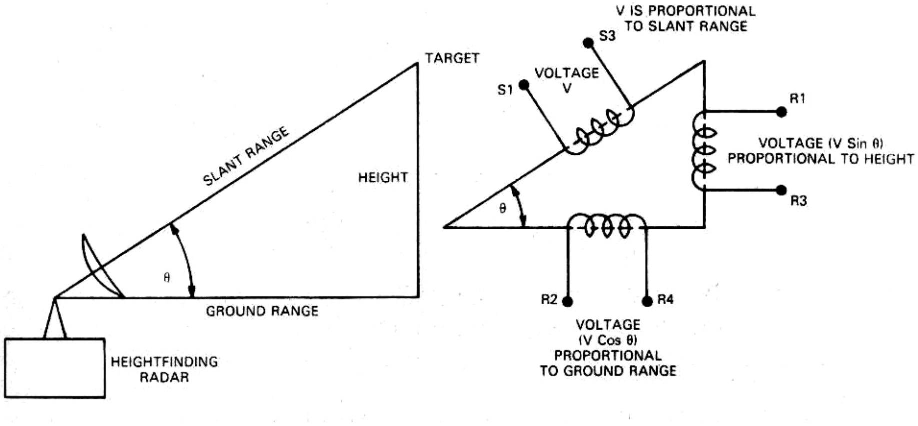


FIG. 1-14 A COMPUTING RESOLVER USED IN A RADAR HEIGHT FINDING APPLICATION.

An example of a Computing Resolver application which uses both rotor windings and both stator windings is in axis transformation.

e.g. Suppose a point in two dimensional space is represented by Cartesian coordinates X_1 and Y_1. If the original axes are rotated through angle ϕ, what are the coordinates of the same point relative to the new axis? ie.X2 and Y2. See Fig. 1-15.

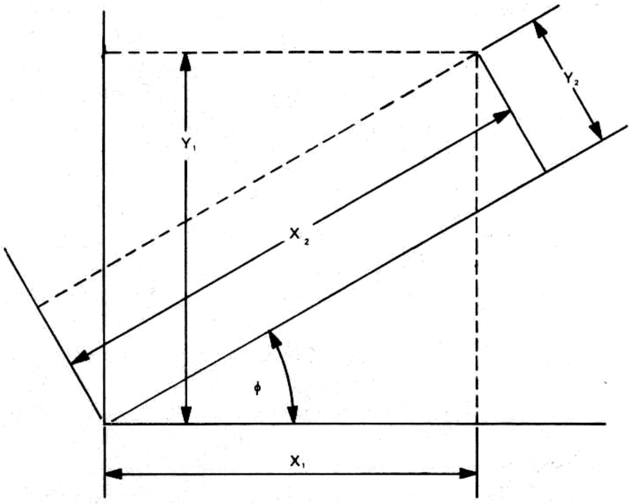


FIG. 1-15 AXIS TRANSFORMATION OF A TWO DIMENSIONAL POINT IN SPACE.

It is easy to show trigonometrically that:

$$X_2 = X_1.\text{Cos}\phi + Y_1.\text{Sin}\phi$$
$$\text{and } Y_2 = Y_1.\text{Cos}\phi - X_1.\text{Sin}\phi$$

If one of the stator windings is excited with a voltage representing X_1 and the other is excited with a voltage representing Y_1, when the shaft is turned through angle ϕ the voltages produced on the rotor terminals will be:

$$V_{R1-R3} = X_1.\text{Cos}\phi + Y_1.\text{Sin}\phi = X_2$$
$$\text{and } V_{R4-R2} = Y_1.\text{Cos}\phi - X_1.\text{Sin}\phi = Y_2$$

The resolver has therefore performed the axis transformation. This application of a computing Resolver is often to be found in guidance systems such as those used in missiles and aircraft.

Feedback Resolvers

The resolvers described above are ideal when the reference voltage is fixed and some phase shift between the reference and signal can be tolerated. Under conditions where the input voltage may be varying, resolvers have been developed with additional windings in the stator slots. The main windings are each supplied from a high gain amplifier which amplifies the difference between the incoming signal and the voltage induced in the feedback winding. The ratio of input to output voltage at any angle will therefore remain constant for a wide range of input levels. The effects of the primary resistance are also eliminated.

Sweep Resolvers

These special resolvers were developed for use in radar displays. Whereas most resolvers exhibit a fairly non linear relationship between reference frequency and transformation ratio, the sweep resolver maintains a constant transformation ratio up to very high frequencies (typically 100 KHz). The triangular waveforms which are required by a radar display can therefore be applied to the stator inputs of the resolver. Similar waveforms modified by the Sine and Cosine of the shaft angle, will be developed in the rotor windings and these can be fed to the deflection coils of the radar display.

VARIATIONS ON THE SYNCHRO AND RESOLVER THEME

The synchros and resolvers discussed so far are the most common and often encountered when dealing with Synchro/Resolver to Digital conversion and Digital to Synchro/Resolver conversion. However, it has taken 40 years for synchros and resolvers to develop into what are undoubtedly the most robust cost effective angular transducers available. It is therefore not surprising that a few variations on the same theme have evolved simultaneously with the standard units. Some of these are described below.

Brushless Synchros and Resolvers

Electromagnetic type

In electromagnetic brushless synchros and resolvers, the rotor signals are transferred to the terminals by means of a circular transformer mounted internally at the end of the unit. There are no physical connections to the rotor and therefore the life of the unit is determined solely by the quality of the bearings. Brushless devices are capable of constant high rotational speeds and exhibit very high M.T.B.F.'s (Mean Time Between Failures). They are also very tolerant as far as the reference frequency and voltage is concerned. In general there is no problem in using electromagnetic brushless devices with Synchro to Digital converters, provided that the appropriate voltages and frequencies are taken into account. One of their main applications is to be found in axis measurement on machine tools, where a lateral movement is translated by means of a lead screw into rotational motion which can then be put into digital format for display or processor use.

Hairspring Synchros and Resolvers

Where only limited movement of the rotor is required, it is possible to use a Hairspring Synchro or Resolver. These are manufactured with spirally wound conductors to pick off information from the rotor. These hairspring conductors allow a rotation of as much as $\pm 165^0$ from the electrical zero position. A mechanical end stop is normally supplied to prevent excessive rotation although this feature very often gives rise to extra unit length. The advantage of the hairspring device over the electromechanical brushless device is that any standard synchro or resolver can be manufactured to a hairspring design without any change in the electrical parameters.   Well designed hairspring devices have very high M.T.B.F.'s and are capable of hundreds of millions of rotational movements without failure.

Because the electrical parameters are similar to standard Synchros and Resolvers, there is no difficulty in interfacing them with synchro/Resolver to Digital converters.

Magslips

Magslips were the forerunners of present day synchros and were developed before World War 2 for gunnery control purposes. The name Magslip is a contraction of "Magnetic slipring". It is generally now accepted that the term "Synchro" embraces Magslips and other instruments working on similar principles, however in this book we will use the word "Magslip" to describe the instruments originally so named. Magslips are generally larger in diameter than synchros and come in frame sizes of 3 inches (76.2 mm), 2 inches (50.8 mm) and 1 ½ inches (38.1 mm). They normally operate on 50 Hz or 60 Hz reference frequencies at 115 volts r.m.s. and produce stator output voltages of 57.5 volts r.m.s..

In a simple control chain, the Magslip transmitter is connected electrically to Magslip Coincidence Transmitter. This is the exact equivalent of the Synchro Control Transformer (CT). Fig. 1-16 shows a Magslip control chain and also indicates the difference in terminal marking between Magslips and Synchros.

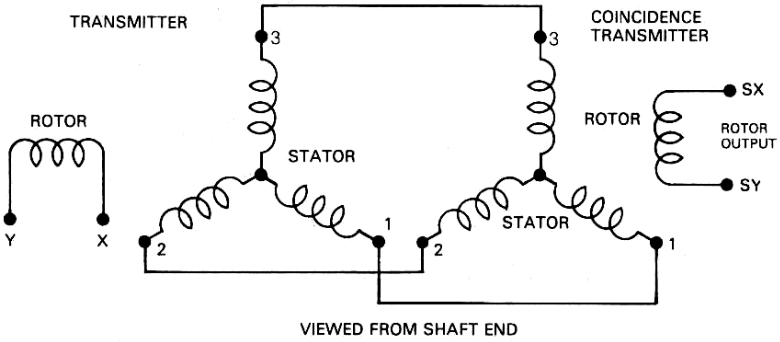


FIG. 1-16 A MAGSLIP CONTROL CHAIN

A Magslip Torque Chain is called a "Synchronous link" and is formed by a Synchronous Link Transmitter and a Synchronous Link Receiver. The transmitter and Receiver are mechanically very similar. A Synchronous Link is shown in Fig. 1-17.

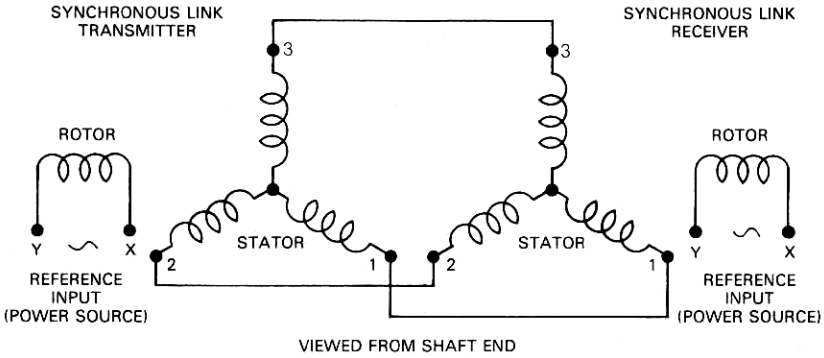


FIG. 1-17. A SYNCHRONOUS LINK

There are two basic differences between Magslips and Synchros apart from those of size, voltage and frequency, which cause problems when interfacing them to Synchro to Digital and Digital to Synchro converters.

The first is that the Magslip standard rotation is clockwise, looking on the shaft end, whereas the Synchro rotation is counterclockwise. If the Magslip Transmitter is used with a Synchro to Digital converter, this problem can be overcome by reversing the S1 and S3 connections, i.e. S1 on the converter goes to terminal 3 on the Magslip and S3 goes to terminal 1.

The second problem, which is not as easy to overcome, is the fact that the rotor of a Magslip is 150 degrees out of alignment with the rotor of a Synchro Transmitter. Therefore if a Magslip Transmitter is connected to a Synchro to digital converter, the digital output will have an offset of 150 degrees. It is often possible to overcome this problem in one of the three following ways:

(1) The Magslip mounting or the mechanical connection to the shaft can be rotated mechanically to compensate for the 150 degrees offset.
(2) If the digital output of the SDC is taken to a processor, the 150 degree offset can be compensated for in the software.
(3) It may be possible to manufacture a special transformer to compensate for the offset, which can be used with a Synchro to Digital converter normally requiring an external transformer.

Transolvers

These are a cross between a Synchro and a Resolver and can convert between 3 wire synchro format voltages and 4 wire Resolver format voltages while at the same time adding or subtracting the rotor angle to the converted output. Transolvers either have 3 winding synchro rotors and 2 winding Resolver stators as in Fig.1-18, or they have a two winding Resolver rotor and a 3 Winding Synchro stator as in Fig.1-19.

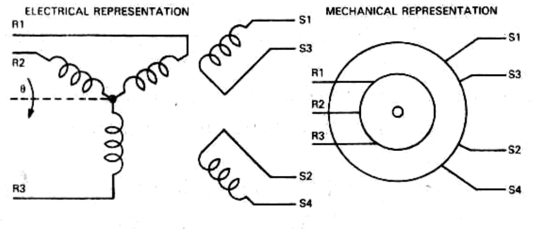


FIG 1-18 TRANSOLVER WITH SYNCHRO ROTOR AND RESOLVER STATOR

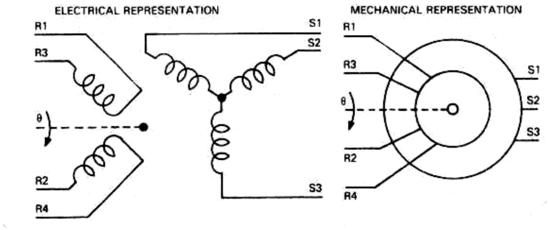


FIG 1-19 TRANSOLVER WITH RESOLVERROTOR AND SYNCHRO STATOR

As far as Transolver to digital conversion is concerned, an ordinary Synchro or Resolver to Digital converter may be used depending on the output format of the Transolver.

Slab or Pancake Synchros and Resolvers

There are many applications where because of physical size limitations or other mechanical constraints, standard synchros and resolvers are unsuitable. For this reason Slab or Pancake Synchros and Resolvers have been developed. The term “Slab” is most often used in the U.K. while “Pancake” is the equivalent term in the U.S.A.. As the name suggests, these devices have a large diameter compared with the width. A typical unit may have an overall diameter of 2.6 inches (66 mm) and a width of 0.45 inches (11.4 mm), although they can go down in size to 1.2 inches (30.4 mm) with a width of 0.25 inches (6.35 mm). Most synchros and resolvers of this type are custom built to fit a particular requirement and as such are often supplied as a separate stator and rotor, the mounting and the bearings being provided by the end user. A classic example of this, is in the use of such components as the angular pickoffs on gyro gimbals. One of the largest manufacturers of Pancake components claims to have over 4000 custom designs in their engineering files. However, most of the manufacturers do offer a fairly comprehensive range of standard units, either as complete housed devices or as a set containing separate rotor and stator.

In general, the winding connections are taken directly off the rotor without the need for sliprings and brushes, as in most applications, for example gyro gimbals, a full 360 degree movement is not required. However electromechanical brushless types are available.

Most Slab devices operate on standard synchro and resolver voltages and frequencies and therefore present no problem as far as converting the output to digital form is concerned.

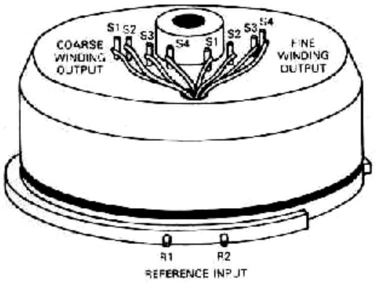


FIG. 1-20 A TWO SPEED SLAB RESOLVER COMPLETE WITH HOUSING AND BEARINGS,

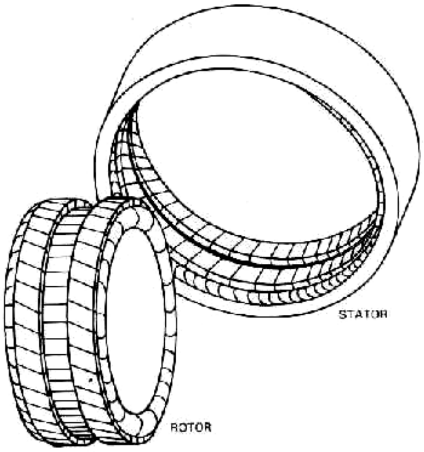


FIG. 1-21 A SLAB RESOLVER SUPPLIED AS SEPARATE STATOR AND ROTOR.

Multipole or Electrically geared Synchros and Resolvers

In cases where it is required to improve the accuracy of a synchro or resolver chain, it is possible to use a two speed or coarse-fine system of transmission.

The traditional method is to transmit the data via two synchros. One synchro (called the coarse synchro) is coupled directly to the main shaft whose angular position is to be transmitted. Another synchro (called the fine synchro) is driven by a step-up gear train, the ratio of which is normally 9:1, 18:1 or 36:1.

Coarse-fine systems are often to be found in applications where an accuracy higher than that obtainable with single speed systems is required and a much more detailed explanation is given in the next section.

However, the traditional method of using a mechanical gearbox to provide the coarse and fine synchro signals suffers from many disadvantages. A much more satisfactory method is to use a multipole Synchro or Resolver. In such a device, one set of windings are wound such that as the shaft is rotated through 3600, the voltage pattern goes through N cycles as though it was a single synchro fitted on the fine shaft of a gearbox with a step-up ratio of N: 1. The other set of windings produce a normal synchro output when the shaft is rotated through 360 degrees. Thus the coarse and fine synchro signals are produced electrically without the need for any mechanical gearing. The advantage of these devices is that they overcome the backlash and gearwheel wear associated with mechanical systems. See Figs. 1-20 and 1-21.

Multipole Synchros and Resolvers are available in any of the common gear ratios normally found in mechanical two speed systems. Because of the number of windings required, they normally come in Slab or Pancake form, although it is possible to obtain them in standard size 18 Synchro frame sizes or larger. Multipole Synchros and Resolvers are normally available with the standard Synchro and Resolver voltage and frequency options, and as such their outputs are very easy to convert into digital form, making them one of the most cost effective and reliable methods available for measuring angular position with accuracies in the order of seconds of arc.

More information on converting the output of coarse fine synchro systems into digital format is given later in this book.

Inductosyns and Rotary Inductosyns

The Linear Inductosyn was developed by Farrand Controls Inc. for the accurate measurement and control of linear distances. It has proved to be one of the most accurate transducers of its type available (0.0001 inches as standard) and is now used by the majority of Numerical control and Machine tool companies for axis control and measurement. The Rotary Inductosyn, as its name implies, is an angular measurement and control transducer based on the same principles as the Linear Inductosyn. It is generally known as being the most accurate angular transducer available with achievable figures of 0.5 Arc Seconds for accuracy, 0.1 Arc Seconds for repeatability and 0.05 Arc Seconds for sensitivity (resolution).

Both Linear Inductosyn and Rotary Inductosyn lend themselves very well to conversion to digital format and over the past few years high speed tracking Inductosyn to Digital converters have been developed which further extend the usefulness of these high accuracy transducers. In this chapter we shall examine the basic principles of Inductosyns and their traditional role, and deal with Inductosyn to Digital conversion in Chapter V. In order to understand the principle of operation, it is best to examine first the Linear Inductosyn.

The Linear Inductosyn

The Linear Inductosyn system consists of two magnetically coupled parts and is similar in operation to a resolver. One part, the scale, is fixed to the axis along which measurement is to take place (e.g. the machine tool bed). The other part, the slider, is arranged so that it can move along the scale in association with the device to be positioned (e.g. the machine tool carrier).The scale consists of a base material such as steel, stainless steel, aluminium etc. covered by an insulating layer. Bonded to this is a printed circuit track forming a continuous rectangular waveform. (In actual fact the scale is usually made up of 10 inch sections which have to be joined together.) The cyclic pitch of the waveform is usually 0.1 inch, 0.2 inch or 2 mm and is formed from two conductive poles. The slider is normally about 4 inches in length and has two separate identical printed circuit tracks bonded to it on the surface which faces the scale. These two tracks are formed from a waveform of exactly the same cyclic pitch as on the scale but one track is shifted of a cyclic pitch from the other ie.900. The slider and the scale are separated by a gap of about 0.005 inches and an electrostatic screen is placed between them. A diagram of the relationship between slider and scale is shown in Fig. 1-22.

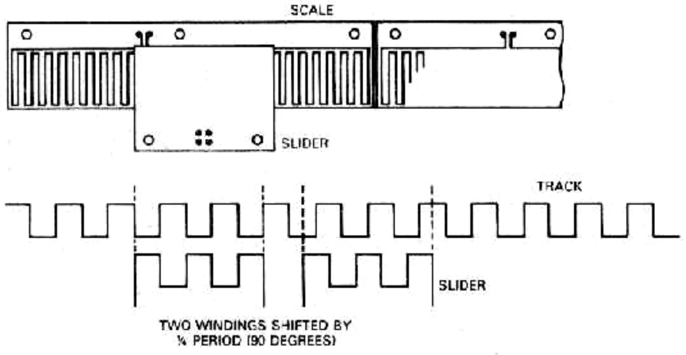


FIG. 1-22 THE RELATIONSHIP BETWEEN THE LINEAR INDUCTOSYN SCALE AND SLIDER.

The principle of operation is not dissimilar from that of the resolver. If the scale is excited by an AC voltage (which is normally between 5 KHz and 10 KHz) V Sin co t, then the outputs from the slider windings will be:

$$V.\sin \omega\, t.\mathrm{Sin}\ 2\pi X/S$$
$$\text{and } V.\sin \omega\, t.\mathrm{Cos}\ 2\pi X/S$$

where X is the linear displacement of the slider and S is the cyclic length.

Therefore the slider voltages are proportional to the sine and Cosine of the distance moved through any one pitch of the scale. The output signals derived from the slider are the result of averaging a number of poles, and therefore the effect of any small residual errors in conductor spacing is compensated. This is one of the reasons why such a high accuracy can be achieved. The magnetic coupling between the slider and the scale is not nearly so high as the coupling between rotor and stator in a resolver, and for this reason the transformation ratio from input to output is very low giving rise to relatively small output signals. A photograph of a Linear Inductosyn scale and slider is shown in Fig. 1-23.

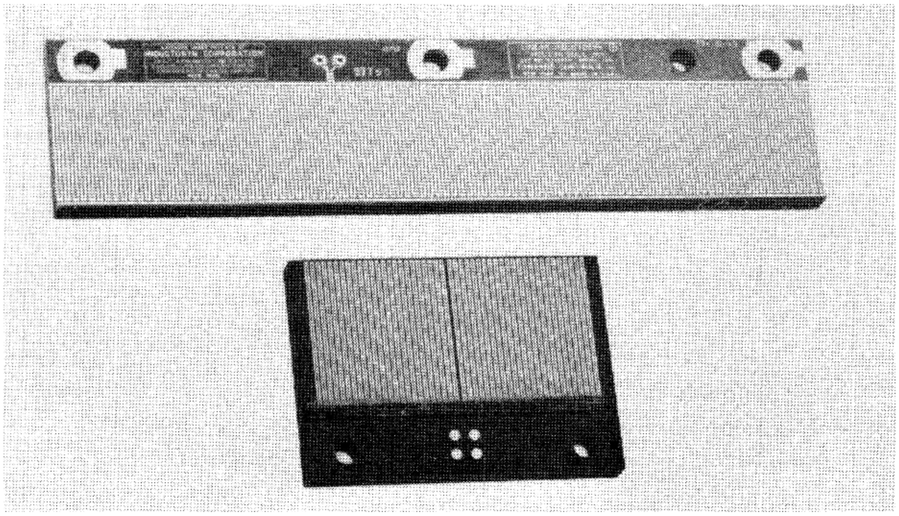


FIG. 1-23 A LINEAR INDUCTOSYN SCALE AND SLIDER.
(Acknowledgements to Inductosyn International Corporation.)

There are three basic ways of using the Linear Inductosyn.
Firstly, it may be used in a Transmitter and Receiver mode in much the same way as a Resolver control chain. In this case, an AC single phase voltage is applied to the scale and the Sine and Cosine voltages appearing on the slider are fed to the slider of the Receiver Inductosyn. The error voltage which is detected on the Receiver scale becomes zero when the transmitter and receiver are in alignment. Thus this error voltage can be used by a servo system in order to drive the slider to the demanded position. Because the Inductosyn consists of a large number of cycles, some form of "coarse" control is necessary to avoid ambiguity. The usual method of providing this is to use a resolver or synchro operated through a rack and pinion or a lead screw.

The second method is to use a resolver with the Inductosyn. This system is shown in Fig. 1-24.

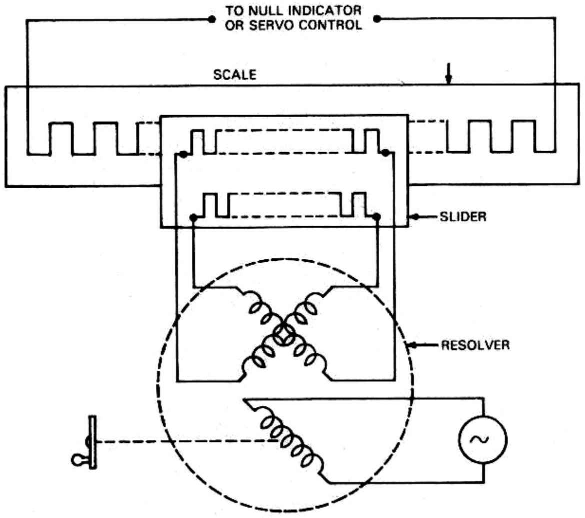


FIG. 1-24 A METHOD OF USING A RESOLVER WITH A LINEAR INDUCTOSYN.

In this method a vernier is attached to the resolver shaft and the stator windings of the resolver are fed to the slider windings of the Inductosyn. As the resolver is turned an error signal will be formed across the scale track depending on the position of the slider in any one cyclic pitch of the scale, i.e. one full revolution of the resolver is equivalent to one cycle of the scale. Thus as the resolver is rotated a servo control system can use the error signal from the scale track in order to move the slider to the demanded position. This method means that positions along the scale can be set to an accuracy of 0.0001 inches. Once again this method is not absolute, i.e. if the power is removed and the slider shifted N periods along the track and the power then reconnected, the same error signal will remain. This can be overcome by having a synchro or resolver on a lead screw acting as the coarse control.

The third method is to use the Inductosyn as a linear transducer in order to provide a digital output for use by a display or a processor. The scale is excited with the AC reference voltage and the slider voltages are fed to an Inductosyn to digital converter which can then be used to drive a display or interface with a processor. Inductosyn to digital converters have now been developed which can handle the high slider speeds which may be demanded and the system can be made absolute by storing the digital positional information in a battery powered random access memory. Thus if the main power supply is interrupted, the information will not be lost. This use of Linear Inductosyns is becoming very common where it is required to replace the existing vernier readouts of machine tools by a digital display in order to increase the accuracy. This use of Inductosyns and Inductosyn to digital converters is also very useful where a digital processor is required to form part of the servo control loop. This will be dealt with in Chapter V.

The Rotary Inductosyn

The stator of a Rotary Inductosyn which corresponds to the slider of the linear device, has the two separate rectangular printed track waveforms arranged radially on a disc. The sine track is made up of a number of sections which alternate with the cosine track. In this way the whole of the stator disc is covered in track and any errors in spacing will be averaged out. This gives the Rotary Inductosyn its exceptionally high accuracy. The rotor of the device corresponds to the scale of the Linear Inductosyn and is a disc with a complete track of near rectangular printed track waveform. The coupling from the rotor to the outside world can be either by sliprings and brushes or by a rotating transformer as in the case of an electromagnetic brushless resolver. Rotary Inductosyns come in diameters of 3 inches, 7 inches and 12 inches and have either 256, 360, 512, 720, 2000 or 2048 poles (2 poles 1 cycle). The units can be supplied as separate stator and rotor disc or as a complete mounted and assembled unit. A photograph of the stator and rotor discs is shown in Fig. 1-25.

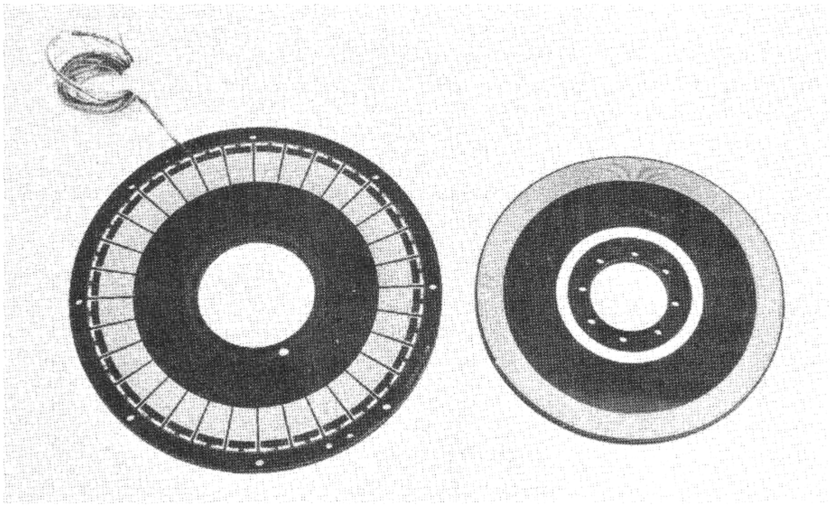


FIG. 1-25 A ROTARY INDUCTOSYN ROTOR AND STATOR.
(Acknowledgements to Inductosyn International Corporation)

When the rotor of the Rotary Inductosyn is excited by the AC voltage, $V \text{ Sin } \omega t$, (normally 5 KHz to 10 KHz), the stator voltages will be

$$V.\text{Sin } \omega t \text{ Sin } N\theta/2$$

$$\text{and } V.\text{Sin } \omega t \text{ Cos } N\theta/2$$

where θ is the angle of rotation of the rotor with respect to the stator and N is the number of poles of the rotor. The Rotary Inductosyn is used in the same three ways as the linear Inductosyn.

Firstly the transmitter and receiver mode in which an AC supply voltage is applied to the rotor of the transmitting Inductosyn and the resulting stator voltages are applied to the stator of the receiving Inductosyn. The output of the receiving Inductosyn rotor is the position error signal, and is zero when the transmitter and receiver rotors arc at complementary positions. Since there are N poles per revolution, there will be N null voltages per revolution. Therefore, to avoid ambiguity, it is necessary to provide a coarse indication of the Inductosyn position as well as a two speed servo system. A conventional synchro or resolver can be used to give the coarse output and a mounting for such is provided in the standard Rotary Inductosyn assembly.

The second method is to use the unit with a resolver as in the case of the Linear Inductosyn. Thus one revolution of the resolver shaft will produce an angle equal to the Inductosyn cycle. The error signal produced on the rotor of the Inductosyn can be used by the servo system to drive the unit to the demanded angle.

The third method is to digitally encode the output of the Rotary Inductosyn in order to provide information for a digital display or processor. As in the case of the linear Inductosyn, high speed tracking Inductosyn to digital converters have been developed which can exploit fully the inherent accuracy of the device. This will be dealt with in Chapter V.

COARSE-FINE SYNCHRO AND GEARED SYSTEMS

When it is required to transmit data more accurately than with a conventional single speed Torque or Control Chain, a two speed or coarse-fine system can be used.

Coarse-Fine Synchro Torque Chains

Consider for example a Torque chain where information is being transmitted from a Torque Transmitter to a Torque Receiver driving a pointer. Such a system is shown in Fig. 1-26.

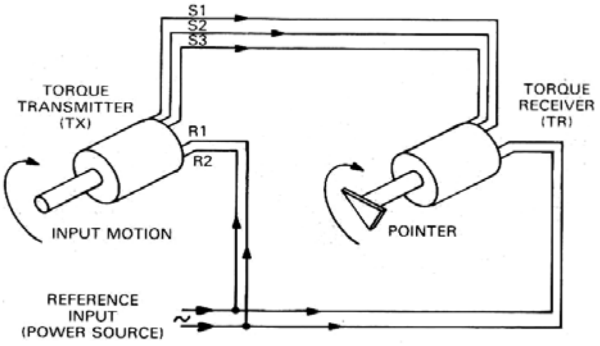


FIG. 1-26 A TORQUE CHAIN DRIVING A POINTER

In such systems, often used in aircraft and ships instruments, the accuracy of data transmission will be around 1%. In applications where this would be excessive, a second display system called the "fine system" may be employed, geared up relative to the first shaft which is then called the "coarse". A common gear ratio for such an application would be 36:1 and the coarse-fine system would then appear as in Fig. 1-27.

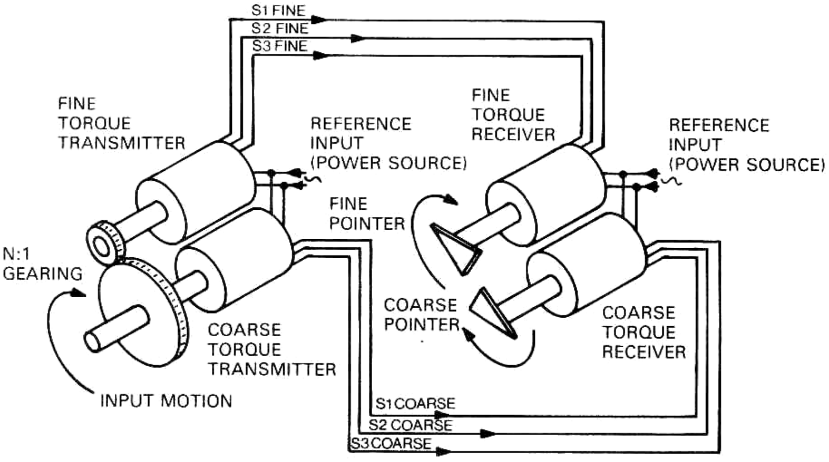


FIG. 1-27 A COARSE-FINE TORQUE CHAIN

In Fig. 1-27, a transmitted angle of l73.6^0 would therefore appear on the coarse dial as being between 170 and 180^0, while the fine dial would read 3.6^0.Because of the high gear ratio used in such a system, the acceleration and speed of the input shaft must be kept within reasonable limits. It is quite common for systems of this type to be updated by replacing the coarse-fine pointer system with a digital display. This requires the outputs from the coarse and Fine Torque Receivers to be digitised and combined together to provide one digital word representing the input shaft angle. More information on coarse-fine digital systems is provided in Chapter III. A technique which is often found, for example, in older radar equipments, is to gear up (say at 36:1) from the main shaft (say the radar antenna) and use it to drive a Torque Transmitter at 36 times the main shaft speed. At the receiving end, (say the radar display) a Torque Receiver uses this information to gear down and so reproduce the original main shaft motion. The advantage of this system is that it reduces the error due to the load torque by N2 where N is the gear ratio. This increases the accuracy of transmission. The disadvantage of such a system is the maximum main shaft angular velocity is restricted to 1. Also if the reference supply is interrupted, ambiguities can arise because there are N possible line up positions. This is overcome in radar systems by having a switch on the antenna which is activated once per revolution, usually at North. This `North Marker' or `North Align' switch closure is used by the radar display to avoid any ambiguities. A system such as this is shown in Fig. 1-28.

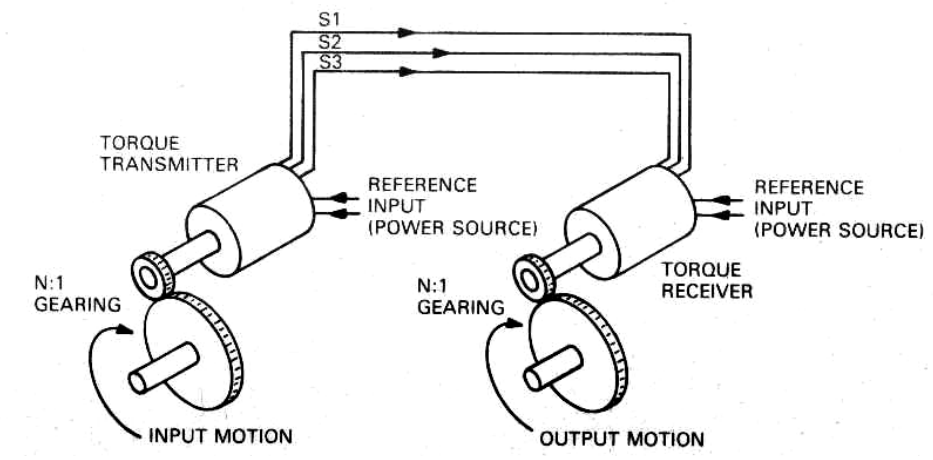


FIG. 1.28 A GEARED SYSTEM WHERE THE FINE INFORMATION ONLY IS TRANSMITTED.

Coarse-fine Synchro control chains

A technique similar to that used in coarse-fine Torque chains can be applied to Control chains. In these systems, two CX's are geared together at ratios which are commonly 9:1, 18:1 or 36:1 in order to transmit the synchro information to 2 CT's which are geared together at the same ratio. A diagram of a coarse-fine synchro control chain is shown in Fig. 1-29.

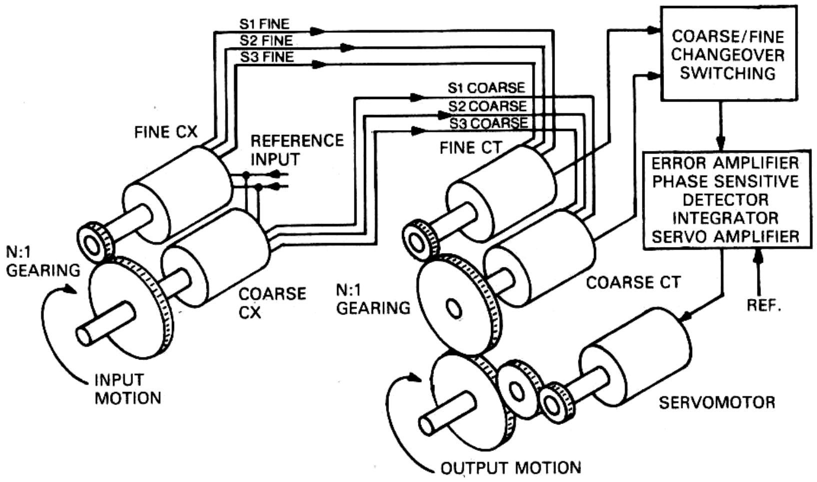


FIG. 1-29 A COARSE-FINE SYNCHRO CONTROL CHAIN.

In a system as shown in Fig. 1-29, the servo motor is controlled by the rotor output of the coarse CT until the misalignment (i.e. the difference between demanded angle and the present angle as represented by the coarse CT) falls below a certain limit. At this point a switchover takes place and the servomotor is then controlled by the fine CT until the demanded angle is reached. during the latter stage, the system is said to be under “Fine control”. The misalignment angle at which the coarse-fine changeover takes place is usually set to between 30 and 150 as referred to the coarse shaft. The most common method of controlling the coarse-fine changeover is by an amplifier and a relay which are permanently connected to the coarse CT rotor. Such a changeover system is shown in Fig. 1-30.

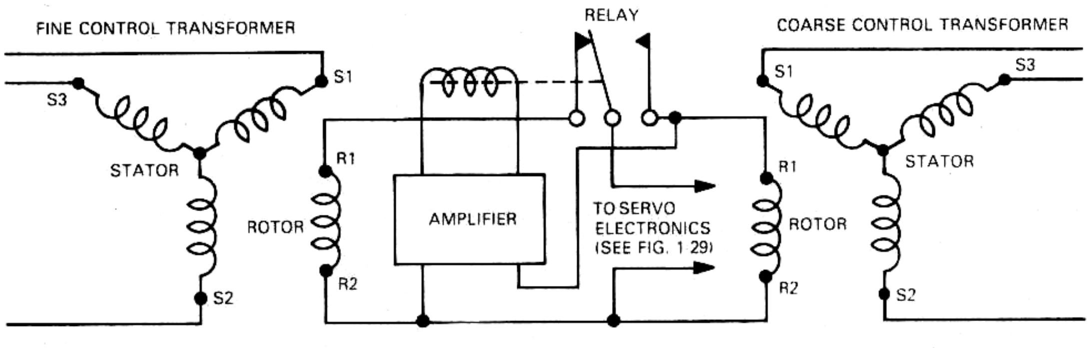


FIG. 1-30 A RELAY METHOD OF COARSE-FINE CHANGEOVER.

With coarse-fine systems such as this, it is possible to transmit angular information representing the motion of the coarse shaft to an accuracy which, in practice, is only limited by the backlash and non-uniformity of the gears referred to the coarse shaft. This means that the synchros used do not need to be of a particularly high precision. To illustrate this further consider the coarse and fine CX's and their gearing. The final positioning of the system depends on the fine synchros only, so let us imagine that we can hold the fine CX rotor fixed. The amount that we can then turn the input shaft will therefore represent the backlash in the gears, say B1.

Assume also that the cyclic errors present in the CX gearing with respect to the input shaft are C1.
If the fine CX has an accuracy of S_t and the coarse-fine ratio is N, then the accuracy of transmission will be:

$$B_t + C_t + {}^{S_t}/_{N}$$

At the receiving end, assume that we hold the fine CT rotor fixed and measure the backlash in the gears B, by detecting the movement on the output shaft.
Assume also that the cyclic errors present in the output gearing with respect to the output shaft are Cr.
Then if the accuracy of the fine CT is S_r the accuracy at the receiving end of the control chain will be:

$$B_r + C_r + {}^{S_r}/_{N}$$

Therefore the accuracy of the system is:

$$B_t + C_t + B_r + C_r + {}^{1}/_{N}. (S_t + S_r)$$

The advantage of a coarse-fine control chain can be easily seen therefore by substituting in the above equation typical values.

e.g. $S_t = S_r = \pm 6$ Arc Min.

$B_t = B_r = \pm ½$ Arc Min.

$C_t = C_r = \pm ¼$ Arc Min.

N = 36:1

Therefore total accuracy of the system is

$$\pm ½ \ \pm ¼ \ \pm ½ \ \pm ¼ \ . \ \pm {}^{12}/_{36} = 1.83 \text{ Arc Min.}$$

The use of anti-backlash gears would make the backlash figures negligible and make the overall system error:

± 0.83 Arc Min. or ± 50 Arc Sec.

This result is considerably better than could be achieved using a single speed method of angular transmission with a CX and a CT each of ± 6 Arc Min. accuracy which would give a total error of ± 12 Arc Min. The accuracy of the system could be increased even more by using a multipole Synchro as the CX. Multipole Synchros are described earlier in this chapter and have overall accuracies typically of 20 Arc seconds with zero backlash.

A disadvantage of coarse fine control systems where an even gear ratio, e.g. 8:1, 16:1, 32:1 or 36:1, is used, is that the system will be susceptible to "false nulls". This means that the servo can in certain cases take up a position 180^0 away from the angle demanded. This is due to the fact that with an even ratio, the voltage gradient produced by the rotor of the fine CT will be in the same direction as at 0^0 with respect to the coarse shaft, as it is at 180^0. This is shown in Fig. 1-31. This means that an unstable coarse null at 180^0 will be accompanied by a fine stable null. Because the system will be under fine control at 180^0 , the output will remain stable at this point and therefore 0^0 and 180^0 are possible as null positions.

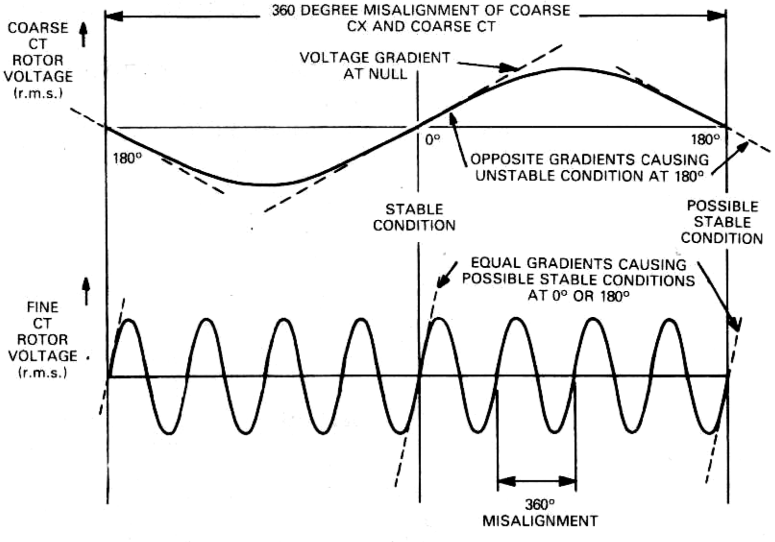


FIG. 1-31 STABLE AND UNSTABLE NULLS FOR EVEN RATIO COARSE FINE SYSTEMS.

This cannot occur with an odd ratio as shown in Fig. 1-32.

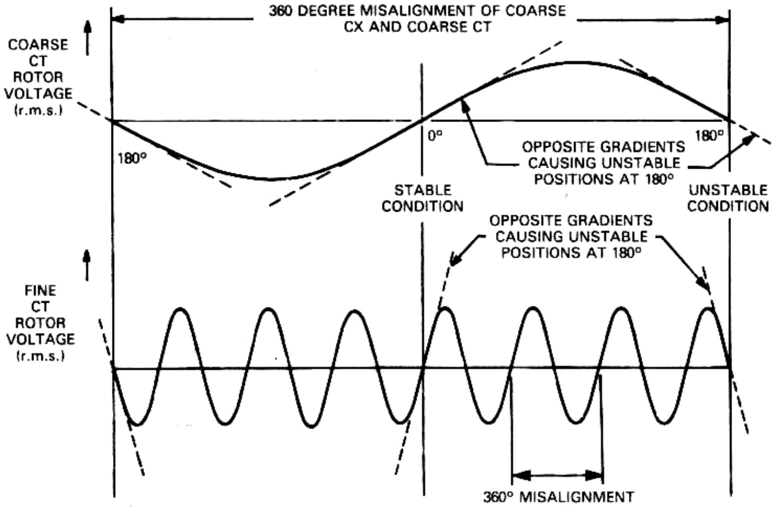


FIG. 1-32 STABLE AND UNSTABLE NULLS FOR ODD RATIO COARSE FINE SYSTEMS.

One method of overcoming the false null situation with even ratio systems is to add an AC voltage (called the "stick off" voltage) into the rotor signal of the coarse CT and compensate by repositioning the stator of the CX or the CT by an amount equivalent to 90^0 of the fine rotation. This means that the coarse CT still passes through the same null at 0^0 but a different null at 180^0. Coarse fine control systems such as those described above are very often found in large servo mechanisms which require a high order of accuracy. Such servo systems would typically be found controlling gun turrets, missile launches or tracking radar.

SYNCHRO AND RESOLVER PARAMETERS

Reference voltages and frequencies

Synchros are usually available for either 60 Hz or 400 Hz operation. The 60 Hz types normally operate with 115 volt r.m.s. reference system while the 400 Hz units are available with 26 volt r.m.s. or 115 volt r.m.s. references. 60Hz Synchros are not available in sizes less than size 15 (1.5 inches diameter) because of the larger windings required, and are most often found in older systems particularly in Naval use.

A 115 volt reference voltage normally gives rise to a 90 volt r.m.s. line to line signal voltage. For example a 115 volt reference applied to 115 volt Synchro control transmitter (CX) will produce outputs between S, S2, and S3 of 90 volts r.m.s. max.

A 26 volt reference voltage normally gives rise to an 11.8 volt r.m.s. line to line signal voltage. Synchro reference frequencies of 512 Hz and I KHz are sometimes encountered.

Part Numbers The symbols used for the various types of Synchros and Resolvers are shown in Fig. 1-33.

Type	**Designation**	**Number of Windings (see note 1)**	**Number of Terminals (see note 1)**
Torque Synchros			
Torque Transmitter	TX	1R/SS	2R/3S
Torque Receiver	TR	1R/3S	2R/3S
Torque Differential Transmitter	TDX	3R/3S	3R/3S
Torque Differential receiver	TDR	3R/3S	3R/3S
Control Synchros			
Control Transmitter	CX	1R/3S	2R/3S
Control Transformer	CT	1R/3S	2R/3S
Control Differential Transmitter	CDX	3R/3S	3R/3S
Resolvers			
Resolver Transmitter	RX	2R/2S	4R/4S
Resolver Differential	RD	2R/2S	4R/4S
Resolver Control Transformer	RC	2R/2S	4R/4S
Transolvers	TY	2R/3S or	4R/3S or
		3R/2S	3R/4S

Note 1: R = rotor S = stator

FIG. 1-33 SYNCHRO AND RESOLVER SYMBOLS.

Synchros and Resolvers have standard type designations (sometimes called military or government designations) which are known and used by all Synchro manufacturers.

The standard type designation is constructed as follows:

(Size) (Type Symbol) (Reference frequency) (Modification State)

4 = 400 Hz a, b, c, d or e
6 = 60Hz

This assumes 115 volt reference operation. If the unit is 26 volt, then 26V precedes the part number. For example:

An 11CT4b is a size 11(1.1 inch diameter) 115 volt, 400 Hz control transformer to a modification state b.
A 26VI1CX4c is a size 11, 26 volt, 400 Hz control transmitter to a mod state c.

In addition to these numbers, all Synchro manufacturers have their own catalogue numbers. For example in the case of an 18CT4c (size 18, 400 Hz, 115 volt control transformer mod state c.) The Muirhead Vactric Ltd part number is 18M2ClQ and the Vernitron corporation number is VCT18-4N1.
Synchros and Resolvers have been well proven as very reliable, robust instruments and they have therefore found their way into many military applications. Because of this many synchros have been allocated, in addition to their other part numbers, NATO stock numbers, US Government drawing numbers and Military Specification numbers (see next section).

Impedances

One of the most important parameters of synchros are the various impedances. The following definitions are universally used and are applied to all synchro devices.

Z_{RO}	Rotor impedance, stator open circuit
Z_{RS}	Rotor impedance, stator short circuit
Z_{SO}	Stator impedance, rotor open circuit
Z_{SS}	Stator impedance, rotor short circuit

For these measurements the rotor is positioned at zero, Z_{RO} and Z_{SO} are measured at normal voltage. Z_{RS}, is measured with the same current in the rotor as in the Z_{RO} measurement. A similar procedure applies to Z_{SS}. When the term "stator impedance" is used it means that impedance which will be measured between one terminal and the other two shorted together. Thus Z_{SO} is shown in Fig. 1-34.

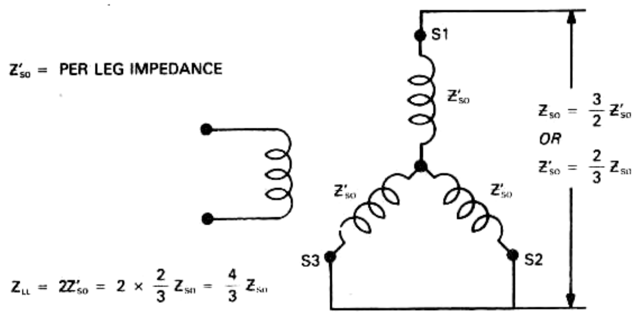


FIG. 1-34 DIAGRAM SHOWING THE MEANING OF Z_{SO}, Z'_{SO} AND Z_{LL}.

Other impedances which are used are:

Z'_{SO} Z'_{SS} etc. meaning the per leg impedance
Z_{LL} is used to denote the impedance between any two lines with the other line open. (This impedance should be qualified according to the rotor condition)
Z_d is the impedance of each arm in the delta equivalent circuit

The relations between these impedances are shown in Fig. 1-35.

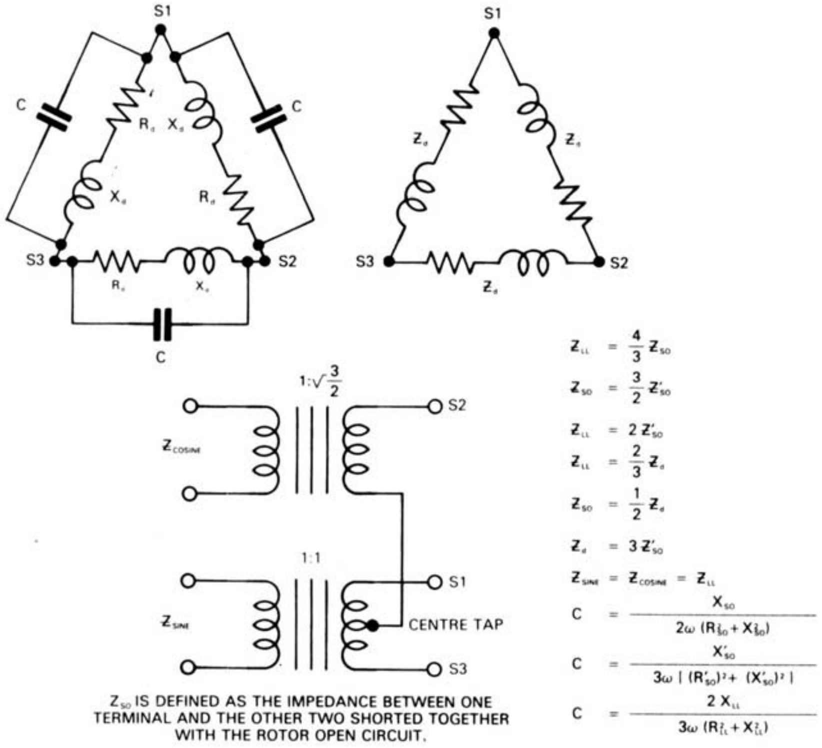
Accuracy

The angular error of a control transmitter is defined as the difference between the rotor position and the angle as defined by the stator voltages. For standard size CX's (i.e. Size 08, 11, 15, 18, 23) this error is normally in the range ±6 Arc Mins. to ± 10 Arc Mins. Depending on the type.

The angular error of a control transformer is defined as the angular amount by which the rotor has to be moved from the angular position as defined by the stator voltages, in order to produce a minimum output. For standard size CT's, this error is normally in the range ± 6 Arc Mins. to ± 8 Arc Mins. depending on the type. A typical Synchro error curve for standard Synchros is shown in Fig. 1-36.

Other types of Synchro (e.g. TR, CDX etc.) have broadly similar accuracies though in general control Synchros are more accurate than Torque Synchros. It is possible to have higher accuracy units available in standard sizes and some manufacturers offer standard Synchros selected for ± 2 Arc Mins. error.

One manufacturer in particular offers a whole range of size 23 control Synchros with accuracy options of 10 or 20 Arc Seconds.



Z_{SO} IS DEFINED AS THE IMPEDANCE BETWEEN ONE TERMINAL AND THE OTHER TWO SHORTED TOGETHER WITH THE ROTOR OPEN CIRCUIT.

$$Z_{LL} = \frac{4}{3} Z_{SO}$$
$$Z_{SO} = \frac{3}{2} Z'_{SO}$$
$$Z_{LL} = 2 Z'_{SO}$$
$$Z_{LL} = \frac{2}{3} Z_d$$
$$Z_{SO} = \frac{1}{2} Z_d$$
$$Z_d = 3 Z'_{SO}$$
$$Z_{SINE} = Z_{COSINE} = Z_{LL}$$
$$C = \frac{X_{SO}}{2\omega (R^2_{SO} + X^2_{SO})}$$
$$C = \frac{X'_{SO}}{3\omega \left| (R'_{SO})^2 + (X'_{SO})^2 \right|}$$
$$C = \frac{2 X_{LL}}{3\omega (R^2_{LL} + X^2_{LL})}$$

FIG 1-35 SYNCHRO IMPEDANCE RELATIONSHIPS

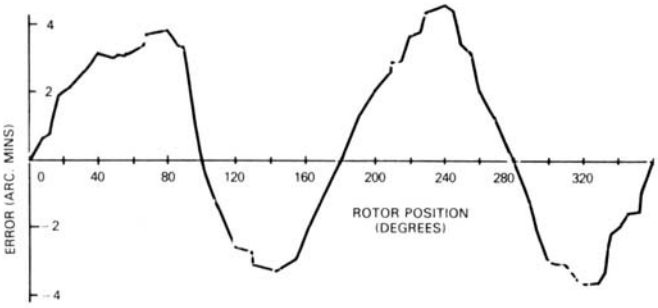


FIG. 1-36 SYNCHRO ERROR CURVE FOR STANDARD SYNCHROS.

However, in general to achieve high accuracies with the single speed devices, it is necessary to use Slab or Pancake Synchros or Resolvers for which accuracies of 20 Seconds are normal and 3 Arc Seconds is achievable.

A table, of the main electrical parameters for all common synchros is contained in Appendix A.

SYNCHRO AND RESOLVER RELIABILITY, ENVIRONMENTAL TESTING AND MILITARY SPECIFICATIONS

Reliability

Synchro and Resolver manufacturers are very reluctant to publish figures for the M.T.B.F. (Mean Time Between Failures) of their devices. This is probably understandable as the failure rate depends on many different factors beyond their control. For example, it is clear that a Brushless Resolver making small infrequent angular movements in an ambient temperature of 250C and a relatively vibration free environment will obviously experience a much lower failure rate than a brush and slipring type resolver rotating at 100 R.P.M. in a 500C ambient temperature environment where a large amount of vibration also exists. The best guide we have therefore to synchro reliability is contained in the USA Department of Defense MIL-HDBK 217A where section 7.8.1 states that many of the factors affecting synchro and resolver failure rate are not normally known to the user. However, the Handbook does define a method of estimating failure rate which takes into account the following factors:

Ambient temperature
Temperature rise of the unit
Type of winding insulation
Size of unit (i.e. Size 11, 15, 18 etc.)
Number of brushes
Type of application
(e.g. Ground, Vehicle mounted ground, shipboard, Airborne, Missile)

These factors influence the calculation to such a degree that it is not possible to state an average M.T.B.F. figure for synchros and resolvers and each case must be treated individually. The following are examples of M.T.B.F. calculations using the method outlined in MIL Handbook 217A section 7.8.3.2 which demonstrate the extremes.

Example 1
An I 1CX4e with class A insulation windings in a 50^0C ambient Ground environment, assuming a temperature rise of 20^0C would have a calculated failure rate of 3.2 failures per million hours or an M.T.B.F. of 312,500 hours or 35 years.

Example 2
An 18CX4d with class A insulation windings in a 25^0C shipboard environment assuming a temperature rise of 20^0C would have a calculated failure rate of 0.325 failures per million hours or an M.T.B.F. of 3,076,923 hours which is 351 years!

Environmental Testing and Military Specifications

There are two main basic specifications which govern the manufacture and type testing of synchros. These are the U.S.A. MIL-S-20708C and the U.K. DEF-STAN 59-27 (Part 90). *These specifications are almost identical*, the slight differences being quoted later. MIL-S-20708C has a different part for each type of synchro approved. These parts are indicated by slash numbers.

For example:

MIL-S-20708/33B is the spec corresponding to an 18CX6C
and MIL-S-20708/2B is the spec corresponding to an 11CX4e.

DEF-STAN 59-27 (Part 90) has different supplements corresponding to each synchro. These supplement numbers, fortunately, correspond numerically to the MLL-S-20708C slash numbers.

For example:
DEF-STAN 59-27 (Part 90) /033 is the spec corresponding to an 18CX6C
and DEF-STAN 59-27 (Part 90) /002 is the spec corresponding to an 11CX4e.

The following information regarding type testing, shows the environmental extremes under which a military specification synchro can operate, and is based on DEF-STAN 59-27 (Part 90) /002 for an llCX4e.

In order for a manufacturer to become an approved supplier of this part, four samples have to be submitted for Qualification Approval Tests. If the tests are successful, then a Qualification Approval Certificate is issued and the manufacturer becomes an approved supplier of synchros to this specification. These tests are very rigorous and although the synchros are required to be in a fully working condition afterwards, the full sequence of tests
could not be used for production testing purposes. For Production Acceptance purposes, a selection of the Qualification Approval Tests are carried out on 100% of the production synchros. These test requirements cover the basic electrical and mechanical parameters of the synchro and do not include for example the shock, vibration, altitude, temperature and endurance tests. In addition to the production testing a certain number of each batch of production synchros are submitted to a selection of the qualification Approval Tests not being used for Production Acceptance purposes.

The Qualification Approval Tests are very detailed and it is only possible here to give a brief summary.

1. The synchro is mounted in the centre of a vertical square metal plate of dimensions 4 inches by 4 inches by 0.1875 inches. This plate is firmly fixed onto a horizontal base plate of dimensions 6 inches by 6 inches by 0.375 inches. (See Fig. 1-37.)

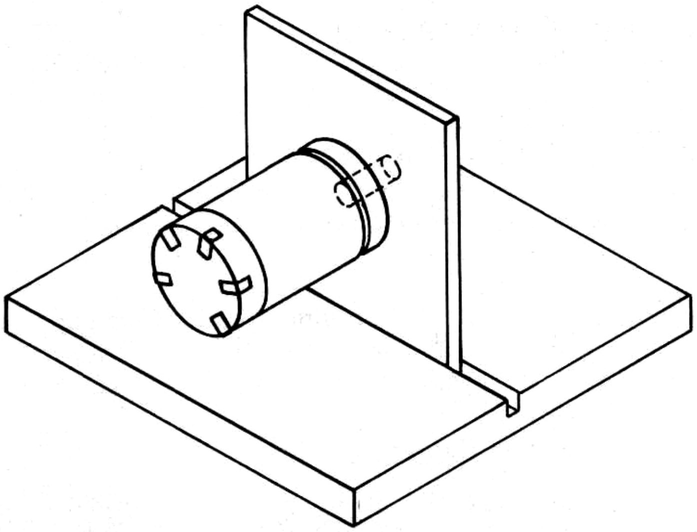


FIG 1-37 SYNCHRO QUALITY APPROVAL TEST MOUNT

2. *Brush contact resistance*
The synchro is energised from a constant current source and the brush contact resistances are checked against the specification.

3. *Mechanical dimensions and finishes*
The synchro is examined to determine whether dimensions and the finishes conform to the particular supplement number data sheet for the unit.

4. *Shaft bearing tolerances*
The shaft radial play of the synchro is checked with a 0.228 Kg load hanging on the shaft. The shaft end play is checked by applying a 0.453 Kg load axially on the shaft in both directions.

5. *Shaft Breakaway torque*
The mechanical breakaway torque of the shaft is also checked.

6. *High voltage insulation*

A 900 volt r.m.s. 50 Hz voltage is applied between the windings and the frame for one minute to check the insulation. The insulation resistance is then checked at -55^{0}C and at ±125^{0}C.

7. *Electrical parameters*

The unit is then energised and the current, power, transformation ratio, phase shift, electrical zero marking (± 10^0), electrical error, null voltage etc. are checked to verify that they conform to the specifications.

8. *Terminal stress*

The terminals are checked by exerting a force of 5 pounds upon them and then examining for damage or movement.

9. *Impedances*

The electrical impedances in the various impedance configurations are then checked.

10. *Temperature rise*

Temperature rise after a period of energisation is measured. In the case of the 1 1CX4e this is 20^{0}C max.

11. *Voltage and frequency variations*

The specification relating to variation in voltage and frequency is then verified.

12. *Electromagnetic Interference*

The synchro is rotated at 1150±50 R.P.M. and checked under load conditions for radiated and conducted electro magnetic interference.

13. *Vibration*

The synchro, on its mounting plate, is energised and an aluminium disc of 2 inch diameter and 0.1875 inches thickness is attached to the shaft. The unit is then subjected to a harmonic vibration of 0.06 inches (1.5 mm) peak to peak amplitude, of peak acceleration of 15 g whichever is the lesser over the range of 10 to 2000 Hz in each of 3 mutually perpendicular planes, one of which is the synchro shaft axis, for a period of 4 hours in each plane. The vibration cycle of 10 to 2000 Hz and return to 10 Hz is traversed in 20 minutes. Any detectable resonance in the brush gear is noted. At the end of this test, the unit is examined for loose or damaged parts.

14. *Low impact shock*

The synchro, still energised and on the mounting plate and fitted with the aluminium disc is then subjected to 5 blows in both directions along 3 mutually perpendicular axes one of which is the synchro shaft axis. Each impact is of 50 g peak acceleration and of an 11 ± 1 mS duration.

15. *Altitude, high and low temperature*

Altitude tests are then carried out on the unit at a simulated altitude of 100,000 ft and temperatures of -55^{0}C and ± 125^{0}C. During these extreme conditions, the synchro is required to pass the tests involving brush contact resistance, shaft radial and end play, mechanical breakaway torque, torque gradient and high voltage and winding insulation resistance.

16. *Endurance*

An endurance test is carried out on the synchro which involves rotation for 1200 hours at 1150 R.P.M. whilst under energisation. The tests involve both clockwise and counter clockwise rotation and on completion it is subjected to the basic mechanical and electrical checks.

17. *Extremes of ambient temperature*

    The unit is energised and allowed to stabilise at an ambient temperature of - 55^0C Whilst at this temperature its basic electrical parameters are checked against the specification. The test is repeated in an ambient of + 125^0C.

18. *Moisture resistance*

    The moisture resistance tests are very detailed and can only be summarised here as follows:

    The energised synchro is subjected to 10 consecutive 24 hour cycles of varying ambient temperature and relative humidity. During the last part of each cycle, the synchro is maintained at 25^0C and at a relative humidity of between 90 and 98%. At the end of each of these periods in the cycle, the temperature of the environmental chamber is lowered to - 10^0C for 3 hours. During this time it is vibrated for 15 minutes with an SHM motion of amplitude 0.06 inches and frequency of 10 to 55 Hz. The synchro is then returned to the ambient of 23^0C $\pm 2^0$C and a relative humidity of 98% before commencement of the next 24 hour cycle. At the end of the 10 cycles, the unit is taken and dried by wiping and shaking but it is not dismantled. It is then left for 24 hours in an ambient temperature of 250C before being subjected to all of the test requirements in the Qualification approval tests.

19. *High impact shock*

    The high impact shock test involves the synchro being energised and fitted along with the aluminium disc into the special mounting. The mounting is then subjected to 3 blows from a weight of 400 lbs. (181 Kgs) falling from a height of 1 ft, 3 ft and 5 ft respectively. A similar test is then carried out by back blows on the mounting from the 400 lb. weight falling from the 3 same distances.

20. *Mould growth and salt spray*

    The testing is completed by performing standard mould growth and salt spray tests. Assuming that all of the above tests are completed satisfactorily the synchro type is then given its Qualification Approval Certificate. The differences between this Qualification Approval and that of MIL-S-20708C is that the latter calls up 2000 hours of rotation at 1150 RPM in the endurance test. There are also slight differences in the electro magnetic interference test.

OTHER ANGULAR TRANSDUCERS

The evolution of the Synchro and Resolver stemmed from military equipment requirements and, as has been shown, the modern units meet the most stringent military specifications. This means that the Synchro and Resolver are unsurpassed as cost effective high reliability angular transducers.

However, other angular transducers do exist and are worthy of mention.

Optical Encoders

Incremental encoders

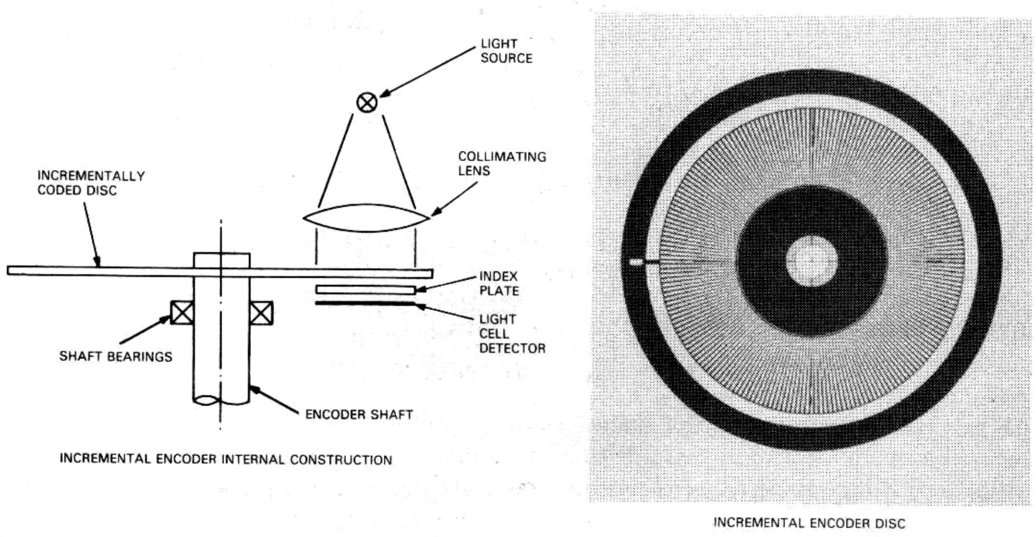
Incremental encoders consist of a disc divided up into alternate optically opaque and transparent sectors, which is driven by the input shaft. A light source is positioned at one side of the disc and a light detector at the other side. As the disc rotates the output from the detector will switch alternately on and off depending on whether an opaque or transparent sector is between the light source and the detector. Thus a stream of square wave pulses is produced, the sum of which at any time indicate the angular position of the shaft. The resolution of the encoder is governed by the number of opaque and transparent sectors and usually falls between 100 and 6000 counts for one complete revolution of the input shaft.

Most incremental encoders feature a second light source and detector, the output of which is phased in such a way in relation to the main detector output, that the direction of the input shaft can be determined. Many encoders also feature a third light source and detector which acts as a once per revolution marker.

Although the output of most encoders such as this are in square wave form, certain types are available with a sinusoidal output from the detectors. This means that the resolution can be increased up to 100 times by interpolation of the sine wave outputs. The construction of an incremental encoder and its associated disc is shown in Fig. 1-38.

Incremental encoders come in sizes ranging from 1 inch diameter (25.4 mm) to 312 inches diameter (88.9 mm). They are also available in all types of external construction ranging from plastic, which is suitable for low cost commercial applications, to stainless steel where the required specification is more rigorous.

While this type of encoder may be useful in some applications it has the disadvantage of having the angular information stored in an external counter. If the information in this counter is lost (for example if the power supply was temporarily interrupted) there is no way of knowing the shaft angle. Also at initial switch on, there is no way of determining the shaft angle until it has been rotated through the revolution marker.



INCREMENTAL ENCODER INTERNAL CONSTRUCTION

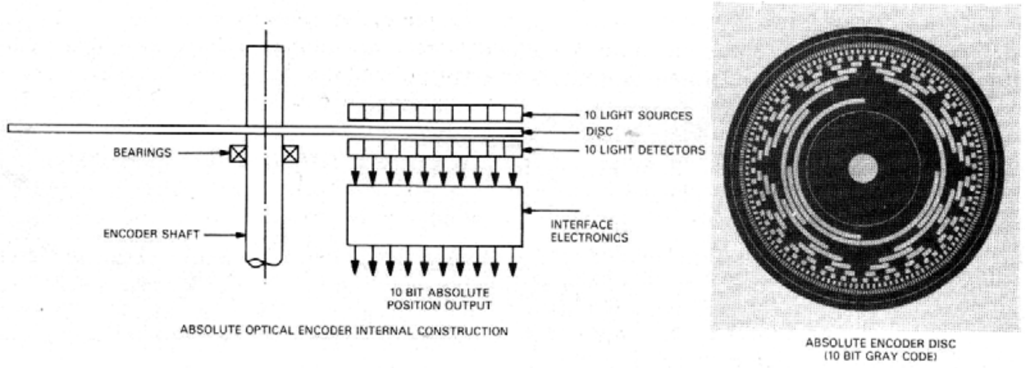
INCREMENTAL ENCODER DISC

FIG. 1-38 CONSTRUCTION AND INCREMENTAL DISC OF AN INCREMENTAL OPTICAL ENCODER.

Absolute encoders

These problems are overcome in the absolute optical encoder. In this device, the disc is divided up into N sectors, each sector also being divided up along its length into opaque and transparent sections forming a digital word with a maximum count of N. The sectors are arranged such that the digital word formed by each set of opaque and transparent sections,

increments in value from one sector to the next. A set of N light sources are arranged radially on one side of the disc and corresponding detectors are positioned on the other side such that a parallel word representing the input shaft angle can be obtained at any one of N angular positions. The construction of an absolute optical encoder is shown in Fig. 1-39.



ABSOLUTE OPTICAL ENCODER INTERNAL CONSTRUCTION

ABSOLUTE ENCODER DISC (10 BIT GRAY CODE)

FIG. 1-39 CONSTRUCTION AND DISC OF AN ABSOLUTE OPTICAL ENCODER.

Therefore the data available at initial switch on immediately gives an unambiguous representation of the shaft angle. Absolute optical encoders come with resolutions of 6 to 16 bits in Gray code, binary or BCD and their sizes vary from 2 inches (50.8 mm) to about 7 inches (177.8 mm) in diameter.

Multiturn Optical Encoders

Optical encoders are available where a high resolution is obtained by gearing together two absolute encoder discs. For example, if a 6 bit disc (i.e. max. count N = 64) driven directly by the input shaft, is geared up at 64:1 to drive a 10 bit disc (max. count N= 1024), then 64 turns of the input shaft will create a full count, on the output, of 65536 (16 bits).These units are suitable in applications where the function to be converted into digital format cannot be accomplished in one turn of the input shaft. Multiturn encoders are available in many sizes, gear ratios and resolutions.

Brush or Contact Encoders

Contact encoders work on a similar principal to absolute optical encoders. However, instead of using a disc where the sections forming the digital word are opaque or transparent, it uses conducting and insulating surfaces in conjunction with brush contacts. This provides a parallel digital word as the output. Obviously this type of encoder is not capable of sustained high rotational speeds and is only suited to applications where the shaft movement is small and infrequent.

Although single speed contact encoders are available with full counts up to 210 (1024), most of them work on the same multiturn principle as is used in multiturn optical encoders, such that a number of turns of the input shaft are required to provide a full count on the digital output.

Contact or Brush encoders vary in size from 1.1 inches (27.9 mm) diameter to 3.3 inches (83.8 mm).

Potentiometers

As the name suggests, these angular transducers require a stable DC voltage as the reference input in order to provide an output voltage which is proportional to angle. As in the case of the contact encoders, the system of integrity of potentiometers relies on brushes making contact with the resistive track and therefore their performance is limited by wear and other mechanical and electrical noise uncertainties.

Both single speed and multispeed potentiometers are available.

Rotary Induction Potentiometers or Linear Transformers

These devices are remotely related to synchros and consist of a rotor with one winding and a stator with one winding. The rotor or the stator can act as the primary which is excited with the AC reference voltage. The output voltage is proportional to the rotor angle. The maximum usable rotor movement is limited to ± 85^0.

COMPARISON BETWEEN SYNCHROS/RESOLVERS AND OTHER ANGULAR TRANSDUCERS

In comparing Synchros and Resolvers (strictly speaking Synchro and Resolver Transmitters) with the other types of angular transducers, it is necessary to include in the assessment the associated electronics required to produce data in the form acceptable for modern control and monitoring systems, that is digital data. All of the transducers considered need some form of interface electronics and this is taken into account in the comparisons.

For example:

Synchros and Resolvers (and Rotary Inductosyns) require an AC reference voltage as well as some electronics to convert from the AC analog output signals into a digital format. Encoders require external electronics, including registers and buffers, as well as common mode rejection circuits to maintain accuracy despite ground loops and induced low frequency noise. Incremental encoders require in addition to this, up-down counting logic.

Potentiometers require a highly regulated power supply as well as Analog to Digital conversion on the output.

Cost Comparison

The relative costs can only be meaningfully compared at a given level of resolution, say 12 bits (5.3 Arc Min.). It is meaningless to compare absolute costs.
The order of decreasing costs will then be:

Absolute optical Encoders
Synchros and Resolvers
Potentiometers
Contact Encoders

Resolution and Accuracy

The approximate maximum attainable accuracies of angular transducers and their associated electronics are shown in the following table.

Type of transducer	**Accuracy**
Rotary Inductosyn	1.5 Arc Sec
Multipole Synchros/Resolvers	7 Arc Sec
High Accuracy Synchros/Resolvers	20 Arc Sec
Absolute Optical encoders	23 Arc Sec
Selected Synchros/Resolvers	3 Arc Min
Standard Synchros/Resolvers	7 Arc Min
Potentiometers *	7 Arc Min
Incremental Optical Encoders	11 Arc Min
Contact encoders	26 Arc Min

*Assuming 14 bit resolution
Note: In the above table, mechanically geared coarse fine synchro/resolver systems have not been included.

Static and Dynamic Mechanical Loading

All shaft angle transducers will present a certain degree of static and dynamic friction to the input shaft. This is much less in the case of the optical encoders and the Synchros and Resolvers (particularly the brushless types) than in the case of the potentiometer and the contact encoders where the friction of the brushes has to be taken into account.

Another factor to contend with is the moment of inertia which the transducer adds to the shaft. In this respect, the miniature synchros and resolvers (site 05, 08 and II) arc far superior to the shaft encoders which require relatively large discs to provide high resolution.

Environmental Considerations

In this comparison, Synchros and Resolvers are unsurpassed. 1'lie combination of synchro and its associated electronics meet more stringent temperature, humidity, shock and vibration specifications than any other shaft angle transducer. This is one of the main reasons why Synchros and Resolvers are preferred for Military and Aerospace applications.

The other transducers (which are all markedly inferior in this respect) are, in descending order of performance, as follows:

Optical encoders
Potentiometers
Contact encoders

Noise Immunity

In most systems involving shaft angle transducers with digital outputs, the processor which requires the data will be separated from the actual shaft where the transducer is fitted. This distance can sometimes be considerable.

In the case of an optical or contact encoder, the digital data will either have to be transferred as a parallel word or transmitted serially and reconstituted at the processor end. Digital data transmitted in this way is very susceptible to corruption by noise. For example there have been cases where digital turning data transmitted from an encoder on a radar antenna to the radar processing equipment has suffered from microwave interference.

Synchros and Resolvers need not suffer from such problems as the 3 or 4 wire analog information is capable of being transmitted over very long distances (up to 2 Km with suitable cable) before being converted to digital format in the vicinity of the processor. If true transformer isolation is used at the conversion end, the line will withstand high common mode voltages and because the conversion will be ratiometric in principle, a very high degree of noise immunity is attained.

As can be seen, Synchros and Resolvers in association with suitable conversion electronics provide the logical choice for angular data measurement and control. the rest of this book therefore is dedicated to the study of the electronics associated with Synchro, Resolver and Inductosyn to Digital conversion and vice versa.

Chapter II -- Scott connected transformers

The representation of angles in digital form, logic inputs and outputs.

INTRODUCTION

Before proceeding to describe the operation and application of Synchro/Resolver to Digital and Digital to Synchro/Resolver converters, it is worth while touching briefly upon three subjects which are particularly relevant when discussing these products.

SCOTT CONNECTED TRANSFORMERS

Modern synchro to digital converters (SDCs) and digital to synchro converters (DSCs) deal internally with signals in resolver format. For this reason it is necessary to convert synchro input signals into resolver form for SDCs and to convert the internal resolver format signals into synchro format in the case of DSCs. These conversions are generally carried out by the use of interconnected transformers known as Scott Connected or Scott Tee transformers. (In the case of the input transformers in a resolver to digital converter and the output transformers in a digital to resolver converter, they do not need to be Scott connected and usually consist of completely separate isolation transformers for sine and cosine channels).

Synchro to resolver format Scott connected transformers

A pair of Scott T transformers connected to perform a synchro to resolver format conversion is shown in Fig. 2-1.

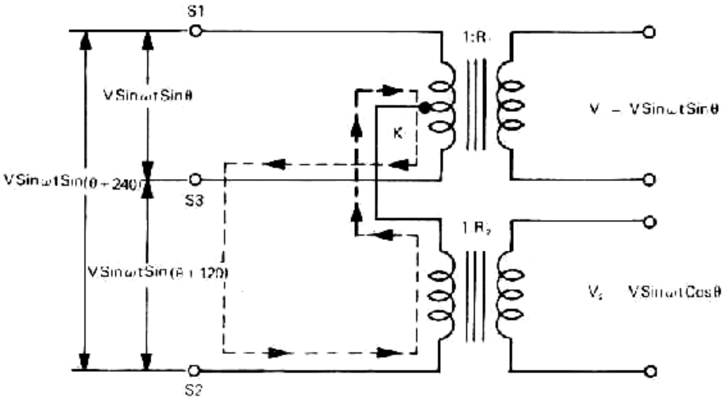


FIG. 2-1 SCOTT CONNECTED TRANSFORMER PAIR. SYNCHRO TO RESOLVER.

As can be seen in the diagram, the synchro format voltages are applied to S1, S2 and S3 of the Scott connected pair and the resolver format output voltages are produced on the two secondary windings. In most practical situations the transformers will also be used to scale the voltages between input and output as well as performing the conversion from synchro to resolver format. This is simply accomplished by increasing the turns on one side or other of each transformer. However in this case we will consider that the transformation ratio of the Scott T pair is 1:1, i.e. the line to line resolver format output voltage will have the same maximum value as the line to line synchro format input voltages.

Referring to Fig. 2-1, the tapped transformer is often known as the "Main transformer" and the untapped one is known as the "Teaser" transformer.

With synchro format input signals, viz.

$$V_{S1-S3} = V \sin\omega t \,.\, \sin\theta.$$
$$V_{S3-S2} = V \sin\omega t \,.\, \sin(\theta + 120^0)$$
$$V_{S2-S1} = V \sin\omega t \,.\, \sin(\theta + 240^0)$$

the output resolver format signals will be:

$$V1 = V \sin\omega t \,.\, \sin\theta$$
$$V2 = V \sin\omega t \,.\cos\theta$$

In a Scott connected pair, it can be shown that the ratio of turns between primary and secondary is 1:1 for the main transformer and 1: $2/\sqrt{3}$ for the teaser. This is assuming that the input maximum voltage equals the output maximum voltage as stated above. It can also be shown that the main transformer is tapped at its midpoint, i.e. the tapping point K = 0.5.
These postulations can be proven as follows:

Let l:R_1 be the turns ratio on the main transformer and l:R_2on the teaser.
The primary voltage on the main transformer is:

$$V \sin\omega t \,.\, \sin\theta$$

Therefore the voltage on the secondary is:

$$V R_1 \sin\omega t \,.\, \sin\theta$$

However, we want to show that:

$$V1 = V.\sin\omega t \,.\, \sin\theta$$

Therefore $\underline{R_1 = 1}$

Concerning V_2 we have:

$$V_2 = VR_2[\text{Sin}\omega t \,.\, \text{Sin}(\theta + 120^0) + K.\text{Sin}\omega t \,.\, \text{Sin}\,\theta]$$

which is obtained by adding the voltages around the arrowed path and multiplying by the ratio R_2.

Taking Sinωt outside gives:

$$V_2 = VR_2\text{Sin}\omega t\, [\text{Sin}(\theta + 120^0) + K.\text{Sin}\theta\,]$$

However:

$$V_2 = V.\text{Sin}\ \omega t \,.\, \text{Cos}\ \theta$$

Which is the resolver format voltage required on V_2

Therefore:

$$V\text{sin}\omega t\ \text{Cos}\ \theta = VR_2\,\text{Sin}\omega t\ [\text{Sin}(\theta + 120^0) + K\text{sin}\ \theta$$

Cancelling out V Sinωt gives:

$$\text{Cos}\ \theta = R_2[\text{Sin}(\theta + 120^0) + K.\text{Sin}\ \theta\,] \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

This must hold for all values of θ, therefore putting $\theta = 0^0$ gives:

$$1 = R_2\text{Cos}\ 30^0$$

Therefore

$$R1 = 1 / \text{Cos}\ 30^0 = {}^2/\sqrt{3}$$

Putting $\theta = 90^0$ into equation (1) gives:

$$0 = {}^2/_{\sqrt{3}}\ [-\text{Sin}30^0 + K]$$

or

$${}^2/_{\sqrt{3}} \,.\, {}^1/_2 = {}^2/_{\sqrt{3}} \,.\, K$$

or

$$K = 0.5$$

Resolver to synchro format Scott connected transformers

Fig. 2-2 shows the resolver to synchro Scott connected transformer arrangement. By the reciprocal theorem, the arrangement is simply the inverse of the synchro to resolver case, the main transformer having a ratio of 1:1 and the teaser a step down ratio of 2A,F3:1. These ratios give the same maximum line to line voltage as the maximum line to line input voltage. As was mentioned earlier, generally both transformer ratios will be scaled in proportion to provide either a step up or a step down ratio as required. Scott transformers are precision components: the design criteria will be influenced by the requirement for the exact ratios.

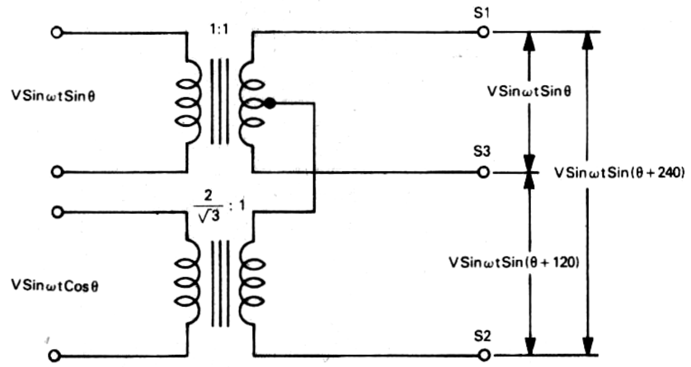


FIG. 2-2 SCOTT CONNECTED TRANSFORMER PAIR. RESOLVER TO SYNCHRO.

The reflected resistance in the Scott connected output transformers of Digital to synchro converters

To avoid the spurious generation of quadrature signals (signals of the same fundamental frequency but with a 90^0 phase shift) in the output transformers of Digital to synchro converters, it is important that the inductive and resistive output impedances of the Scott connected pair of transformers should be equal in each of the three output wires S1, S2 and S3. By choosing suitable wire gauges, the secondary resistance can be made equal. The question arises about the primary resistance when reflected to the secondary side. The primary turns are equal and for similar wire gauges the primary resistances will be equal and by design the output impedances of the driving amplifiers can be made equal. The question is, do these equal primary resistances give rise to equivalent equal resistances in the three secondary wires?

Fig. 2-3 shows the resistance on the primary side and Fig. 2-4 shows the resistances in the secondary side due to the primary resistance.

The resistance between S_1 and S_3 will be $R_p .\ N^2$

Therefore $R_1 = R_2 = R_p . \, {}^{N^2}/_{2}$

The resistance between S_1 and CT will be $R_p. \left({}^{N}/_{2} \right)^2$ where CT = Midpoint Tap

Therefore the resistance in series with the CT will have to be negative and equal to:

$$- Rp \ . \, {}^{N^2}/_{2}$$

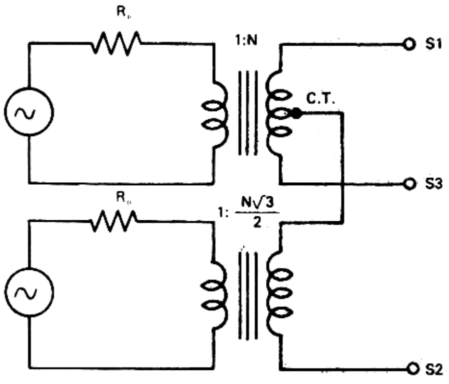


FIG. 2-3

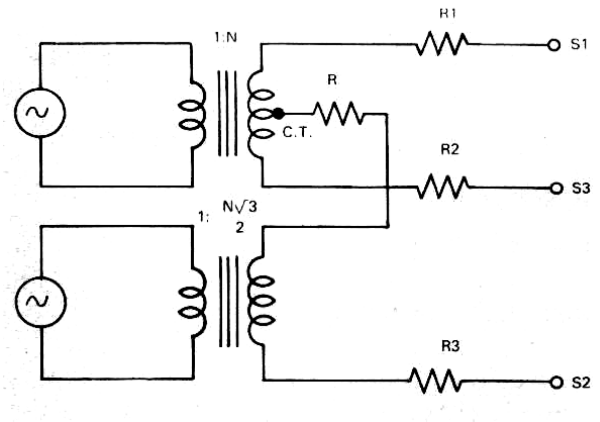


FIG. 2-4

The resistance R_3 is equal to $R_p . \, {}^{3}/_{4} . N^2$

Checking the resistances between S_1, S_2 and S_3 we have:

$$S1 \text{ to } S3 = Rp . N^2$$

$$S1 \text{to } S2 = R_P. \, {}^{N^2}/_{2} - Rp. \, {}^{N^2}/_{4} + Rp \, {}^{3}/_{4} . N^2 = R_p . N^2$$

$$S3 \text{ to } S2 = R_P. \, {}^{N^2}/_{2} - Rp. \, {}^{N^2}/_{4} + Rp \, {}^{3}/_{4} . N^2 = R_p . N^2$$

Therefore the answer to the question is that if the primary resistances are equal, they give rise to equal equivalent resistances on the secondary side. The necessary balancing of the resistances to reduce to a minimum the introduction of quadrature signals can therefore be carried out by resistive balancing of the secondary windings only. (See Section on quadrature errors in DSCs in Chapter 4.)

The use of Scott connected transformers as the input to synchro to digital converters

When used as the input transformers in synchro to digital converters, the input impedance of the amplifiers at the converter side of the input Scott connected pair of transformers is very high, so high in fact that it does not contribute in any significant way to the loading on the input signal lines. The loading on the lines is determined by the primary reactances and resistances in series. The primary reactance is very high compared with the resistance, it is so high in fact that when the Scott connected transformers are driven from the low output impedances from Control Transmitters that a considerable out of balance is required before any significant errors occur. The point being made however is that in this case if we are to seek balanced loading on the lines it is the primary inductances and not the resistances of the windings which is the dominating factor. To provide some figures a low voltage CX size 11 could have an output Zss of 9 +j3 ohms (Zss is Z stator, rotor shorted) or an output Zso of 8 +j45 Zso is (Z stator rotor open). (Which of these impedances is relevant will depend on whether the rotor is voltage or current driven.) If we take the worst case of Zso of 8 ± j45 this corresponds to a Z_{LL} of 10.7 +j60. (Z_{LL}= 4/3 Zso). This impedance must be compared with 20 K ohms which is a typical low voltage line to line impedance.

The line to line impedances which are of the order of 20 K ohms (nearly purely reactive) must be balanced to give the required accuracy when driven from sources of between 10 and 60 ohms line to line. The balance required is on the inductances of the synchro input to the Scott connected transformers. Fig. 2-5 shows the arrangement which gives this inductive balance.

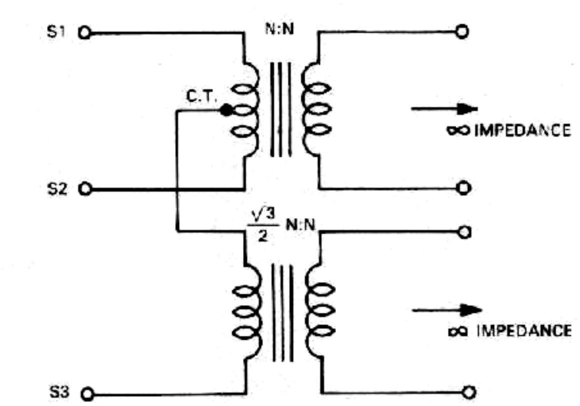


FIG. 2-5 SCOTT CONNECTED TRANSFORMERS WITH BALANCED INDUCTANCES.

Inductance between S1, S2 = KN^2
Inductance between S2, S3 = $K(1/2 \times N)^2 \pm K(\sqrt{3}/2 \times N)^2$
$= KN^2$
Inductance between S1, S3 = $K(1/2 \times N)^2 \pm K(\sqrt{3}/2 \times N)^2$
$= KN^2$

The inductive balances depend upon the same core size and material being used for each transformer (the same K for each transformer). Since the same core sizes are required identical transformers can be used with tappings on the primary for the CT and the f3/2 point. With this arrangement the resistances are not balanced (they could be by using differing wire gauges) but since their effect is negligible it is of no consequence.

Electronic Scott T transformers

It is possible to carry out these Synchro to resolver format conversions and vice versa without the use of transformers at all. This is done by operational amplifiers and is often referred to as an Electronic Scott T. However, the need in synchro systems for a high voltage common mode rejection makes the transformer method preferable and in some cases, for example in aircraft systems, mandatory.
None of the products discussed in this book use electronic Scott Ts.

THE REPRESENTATION OF ANGLES IN DIGITAL FORM

Binary coding

There are many possible methods of representing angular information in digital form. By far the most common, and that used in all of the binary input and output products discussed in this book is natural binary coding. In this system of coding, the Most Significant Bit (MSB) represents 180^0, while the next represents 90^0, the next 45^0 and so on. The value of the Least Significant Bit (LSB) will depend on the number of bits in the digital word (word length). Word lengths used will depend on the accuracy and the resolution required and in the case of SDC’s and DSC's will usually lie in the range of 10 to 20 bits.

The digital word is usually represented in positive logic where a “1” state indicates that the particular bit is included in the word and a”0,” state indicates that it is not.

An example of an angle represented in natural binary coding is 257.960 which would be represented in a 12 bit word as follows:

101101110111
MSB LSB

Fig. 2-6 shows the bit weights for words up to 20 bits in length.

		Angle in.		
Bit No	Angle in degrees, decimal	Degrees	Arc. Min.	Arc. Sec.
1	180.00000	180	0	0.0
2	90.00000	90	0	0.0
3	45.00000	45	0	0.0
4	22.50000	22	30	0.0
5	11.25000	11	15	0.0
6	5.62500	5	37	30.0
7	2.81250	2	48	45.0
8	1.40625	1	24	22.5
9	0.70313	0	42	11.3
10	0.35156	0	21	5.6
11	0.17578	0	10	32.8
12	0.08790	0	5	16.4
13	0.04395	0	2	38.2
14	0.02197	0	1	19.1
15	0.01099	0	0	39.6
16	0.00549	0	0	19.8
17	0.00275	0	0	9.9
18	0.00137	0	0	4.9
19	0.00069	0	0	2.5
20	0.00034	0	0	1.2

FIG. 2-6 BIT WEIGHTING IN NATURAL BINARY FOR WORD LENGTHS UP TO 20 BITS.

B.C.D. Binary coded decimal

When angles have to be displayed in digital form, it is often convenient to have the input to the display in Binary coded decimal format. The B.C.D. coding for angles is as for other B.C.D. codes where each decimal digit is formed from a group of four binary coded bits. The groups of four binary digits represent the following angular ranges:

0.00^0 to 0.09^0 in 0.01^0 increments
0.0^0 to 0.9^0 in 0.1^0 increments
0.0^0 to 9.0^0 in 1^0 increments
00^0 to 90^0 in 10^0 increments

000^0 to 300^0 in 100^0 increments

Note, in a system requiring a full scale output of 00 to 359.99^0, only 2 bits are required in the 100^0 group. In a system requiring 0^0 to $\pm 180^0$, only 1 bit (the 100^0 bit) is required in the 100^0 group, the second bit in this group is generally used as the sign bit.

The advantage of the B.C.D. method of coding for display purposes is that the seven segment decoders that go with the displays each only require inputs from four binary bits.

When the output from a synchro to digital converter is required both for computation and for display, it is usual to use an SDC giving a binary output followed by a Binary to B.C.D. converter for producing the display data. When the data is used only for display purposes, Synchro to digital converters are available which give the B.C.D. data directly.

An example of an angle represented in Binary coded decimal form is 276.4^0 which would be:

10 0111 0110 . 0100
(2 7 6 . 4)

Machine tool scaling (4000 counts)

Machine tool control applications sometimes demand that a full revolution of 360^0 is represented by 4000 counts. The requirement stems from the fact that the inputs are usually in inches or metric units and divisions of the basic unit into 4000 parts (divisions of 2000 and 1000 are automatically achieved) leads to more easily interpreted sub units.

When the output scaling is in 4000 counts per revolution, the output is often used in serial form with an additional pulse once per revolution for setting the datum point. In addition to the serial output, a level is provided which indicates the direction of rotation. Since the applications of this type of converter are such that many revolutions are often used to represent the movement involved, external counters are used which count the pulses within the 360^0 as well as the total number of revolutions.

Military scales (6400 counts)

In some military applications, particularly those involving artillery, it has been found convenient to use the scale of 6400 counts representing 360^0. As a consequence of this, Synchro to digital converters are available where the output has a full scale value of 6400 or 6400.0 represented in Binary Coded Decimal.

Degrees and Arc. Minutes

It is sometimes necessary to display an angle in degrees and arc. minutes instead of degrees and fractions of a degree.. This is done with a B.C.D. representation in a similar way to the degrees and fractions method. For example, 276^0 45' would be:

10 0111 0110 0100 0101
(2 7 6^0 4 5')

Various products are available to perform the binary to Degree and arc. minute B.C.D. conversion.

LOGIC INPUTS AND OUTPUTS

Logic types

The products discussed in this book use three main digital input/output types, namely Standard TTL, Low power Schottky TTL (L.S.) and Buffered three-state. The loading details given in the data sheets are given in terms of how many TTL loads the devices are capable of driving in the case of outputs and how many TTL loads they present in the case of inputs.

Because different rules apply to each type of digital output as far as interfacing is concerned, a list of the output devices used internally in each product featuring a digital output is given below. When considering the interfacing and lead length limitations, the information below should be used in conjunction with the data in the appropriate data sheet. It should also be remembered that in most cases a certain amount of the logic output device drive capability is used internally by the converter.

Standard TTL

Product	Output logic device type
SBCD1752	MM5331 (Monolithic Memories Inc)
SBCD1753	MM5331 (Monolithic Memories Inc)
SBCD1756	MM5331 (Monolithic Memories Inc)
SBCD1757	MM5331 (Monolithic Memories Inc)
SDC1602	54193
SDC1603	54193
SDC1604	54193

Low power Schottky TTL

Product	Output logic device type
SDC 1700	54LS 191
SDC 1702	54LS 191
SDC 1704	54LS 191
TSL 1612	54LS 83

In these devices it is suggested that the user incorporates adequate signal transmission techniques to retain the noise immunity performance of the low power Schottky family.

Product	Output logic device type
SDC 1725	54L5374 and 54LS 173
SDC 1726	54LS374 and 54LS 173
SDC 1741	54LS374 and 54LS 173
SDC 1742	54LS374 and 54LS 173

These devices, being Three-state possess the added advantage of buffered outputs.

In interfacing all three categories of products described above over long distances, the use of Schmitt trigger devices, such as the LS132, is advocated at the receiving end.

Note that all the devices mentioned above are used by the extended (military) temperature range products.

Interfacing TTL outputs with CMOS devices
As inputs, CMOS logic levels are as below:

Logic `1' state greater than 0.7 VDD
Logic `0' state less than 0.3 VDD

where VDD is the highest rail voltage applied to the CMOS device.

When it is required to interface TTL outputs into CMOS devices, an amplification of the logic state changes will be required. A suitable device for doing this is the SN5406, of which one sixth can be used per bit.

This is shown in Fig. 2-7.

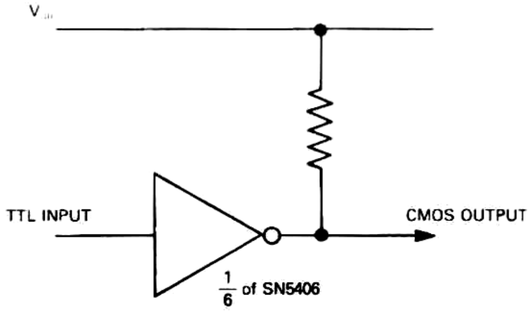


FIG. 2-7 INTERFACING A TTL DEVICE TO A CMOS DEVICE.

Other alternative circuits can be found in chapter 5, vol. 3 of `Semiconductor Circuit Designs published by Texas Instruments Inc.

SYNCHRO AND RESOLVER CONNECTION CONVENTIONS

Introduction

Synchro control transmitters and control transformers each have five wires connected to them. i.e. S1, S2, S3, RI and R2. Concerning the possible permutations of the ways that the wires may be connected, there are two ways that the reference can be connected and for each of these there are six ways that the three signal wires may be connected.

In the case of resolvers, there are S1, S2, S3, and S4 together with R2(R1) and R4(R3). (i.e. most resolvers have two rotor windings.) Concerning the number of ways of connecting these there are two ways for the reference and for each of these there are two ways for S1 and S3 and for each of these there are two ways for S2 and S4. i.e. there are eight permutations after the three pairs of wires have been sorted out.

Below are definitions which are adopted for the voltages between S1, S2. S3 and S4 and the reference for synchro and resolver use which should remove some of the possible alternatives.

Synchro definitions

Fig. 2-8 shows how the voltages between the various pairs of wires vary with the output angle of a Singer Gertsch Synchro/Resolver Standard. The positions of the suffixes in the equations is important. A way of defining the voltages which makes the meaning of the suffixes clear is: If S1 is connected to R2 and both are connected to a dual trace oscilloscope common arid S3 is displayed on one trace with R1 displayed on the other trace, the carrier voltages will be in time phase in the first angular quadrant.

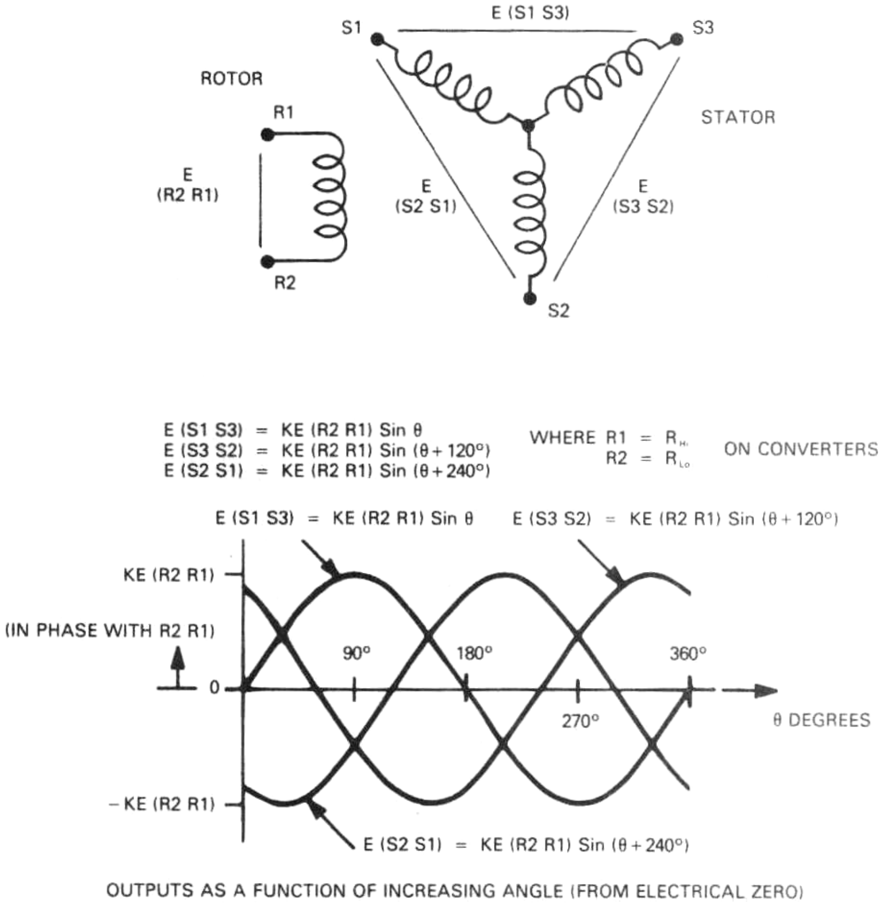


FIG. 2-8 SYNCHRO CONNECTION CONVENTION.

Resolver definitions

Fig. 2-9 shows how resolver voltages vary with the output angle of a Singer Gertsch Decade Synchro/Resolver Standard. An alternative way of stating the resolver voltage convention is:

If S3, S4 and R4(R3) are connected together and to a dual trace oscilloscope common, then S2(S1) is in phase with R2(R1) and S1(S4) is 180^0 out of phase with R2(R1) in the first angular quadrant.

Fig. 2-10 shows the relationship between the voltages on the resolver to digital converters and the synchro to digital converters relative to the Decade Synchro/Resolver standard* All the converters discussed in this book are calibrated using this type of instrument.

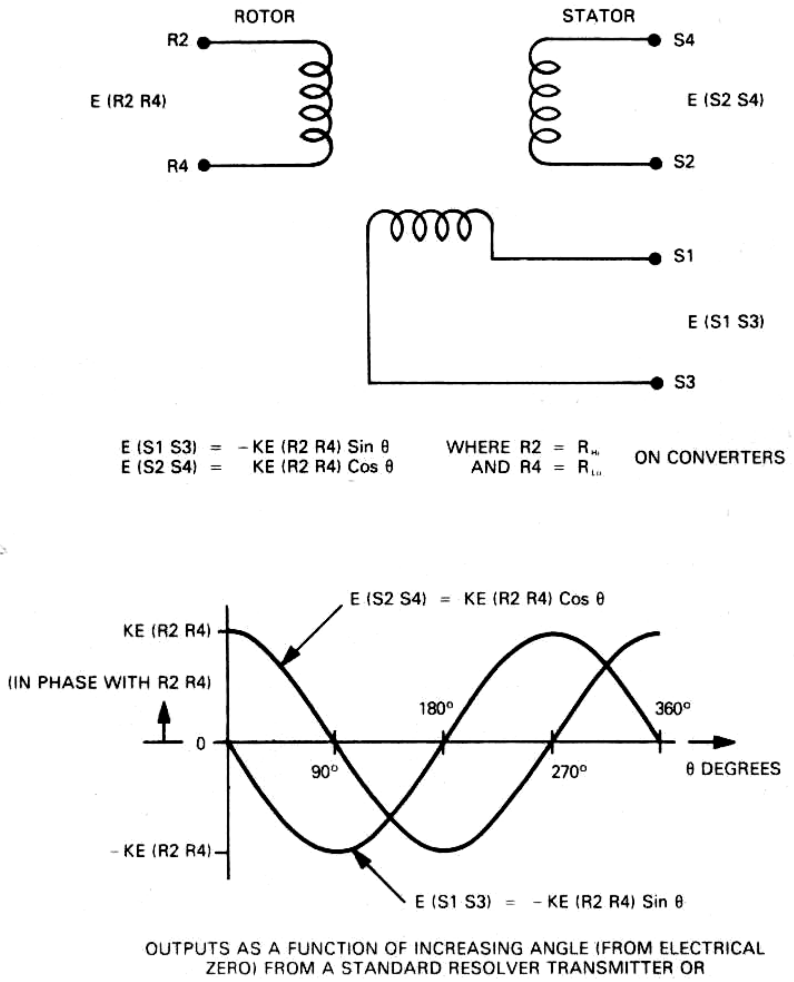


FIG. 2-9 RESOLVER CONNECTION CONVENTION.

STANDARD	R2 (R1) RESOLVER I/P	R4 (R3) RESOLVER I/P	S1 (S4) Sin θ	S2 (S1) Cos θ	S3 (S2) Sin θ	S4 (S3) Cos θ
R/D CONVERTER	R_{HI}	R_{LO}	S1	S2	S3	S4
RESOLVER CONNECTIONS						

STANDARD	R1 SYNCHRO I/P	R2 SYNCHRO I/P	S1 SYNCHRO O/P	S2 SYNCHRO O/P	S3 SYNCHRO O/P
S/D CONVERTER	R_{HI}	R_{LO}	S1	S2	S3
SYNCHRO CONNECTIONS					

FIG 2-10 DECADE SYNCHRO/ RESOLVER STANDARD.*

* The original handbook gave the Singer Gertsch as the Decade Standard which is no longer available however an equivalent instrument is available from North Atlantic Industries.

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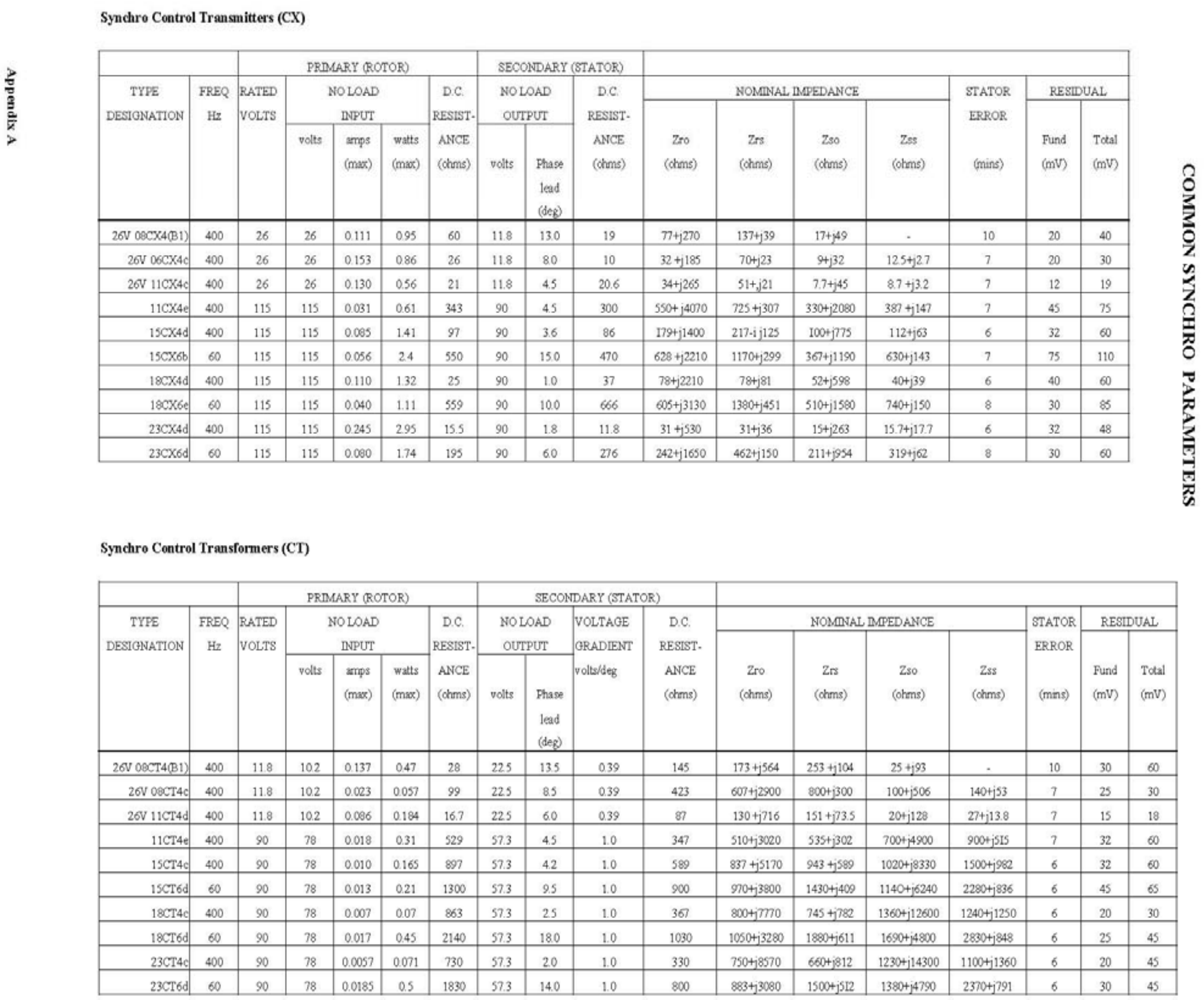
Appendix A



Appendix A

Appendix A

COMMON SYNCHRO PARAMETERS

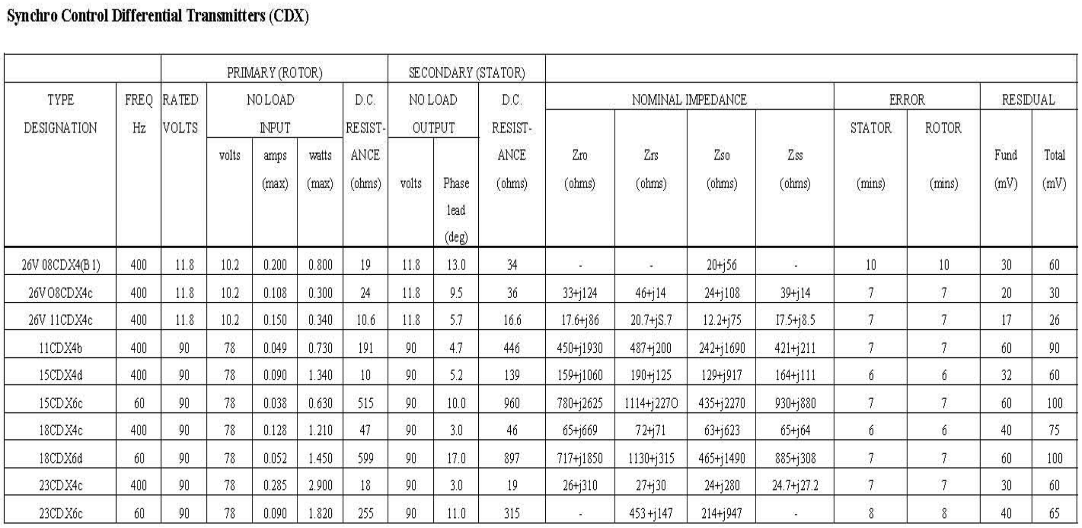
Synchro Control Transmitters (CX)

		PRIMARY (ROTOR)					SECONDARY (STATOR)									
TYPE DESIGNATION	FREQ Hz	RATED VOLTS	NO LOAD INPUT			D.C. RESIST-ANCE (ohms)	NO LOAD OUTPUT		D.C. RESIST-ANCE (ohms)	NOMINAL IMPEDANCE				STATOR ERROR (mins)	RESIDUAL	
			volts	amps (max)	watts (max)		volts	Phase lead (deg)		Zro (ohms)	Zrs (ohms)	Zso (ohms)	Zss (ohms)		Fund (mV)	Total (mV)
26V 08CX4(B1)	400	26	26	0.111	0.95	60	11.8	13.0	19	77+j270	137+j39	17+j49	-	10	20	40
26V 06CX4c	400	26	26	0.153	0.86	26	11.8	8.0	10	32 +j185	70+j23	9+j32	12.5+j2.7	7	20	30
26V 11CX4c	400	26	26	0.130	0.56	21	11.8	4.5	20.6	34+j265	51+j21	7.7+j45	8.7 +j3.2	7	12	19
11CX4e	400	115	115	0.031	0.61	343	90	4.5	300	550+ j4070	725 +j307	330+j2080	387 +j147	7	45	75
15CX4d	400	115	115	0.085	1.41	97	90	3.6	86	179+j1400	217-i j125	100+j775	112+j63	6	32	60
15CX6b	60	115	115	0.056	2.4	550	90	15.0	470	628 +j2210	1170+j299	367+j1190	630+j143	7	75	110
18CX4d	400	115	115	0.110	1.32	25	90	1.0	37	78+j2210	78+j81	52+j598	40+j39	6	40	60
18CX6e	60	115	115	0.040	1.11	559	90	10.0	666	605+j3130	1380+j451	510+j1580	740+j150	8	30	85
23CX4d	400	115	115	0.245	2.95	15.5	90	1.8	11.8	31 +j530	31+j36	15+j263	15.7+j17.7	6	32	48
23CX6d	60	115	115	0.080	1.74	195	90	6.0	276	242+j1650	462+j150	211+j954	319+j62	8	30	60

Synchro Control Transformers (CT)

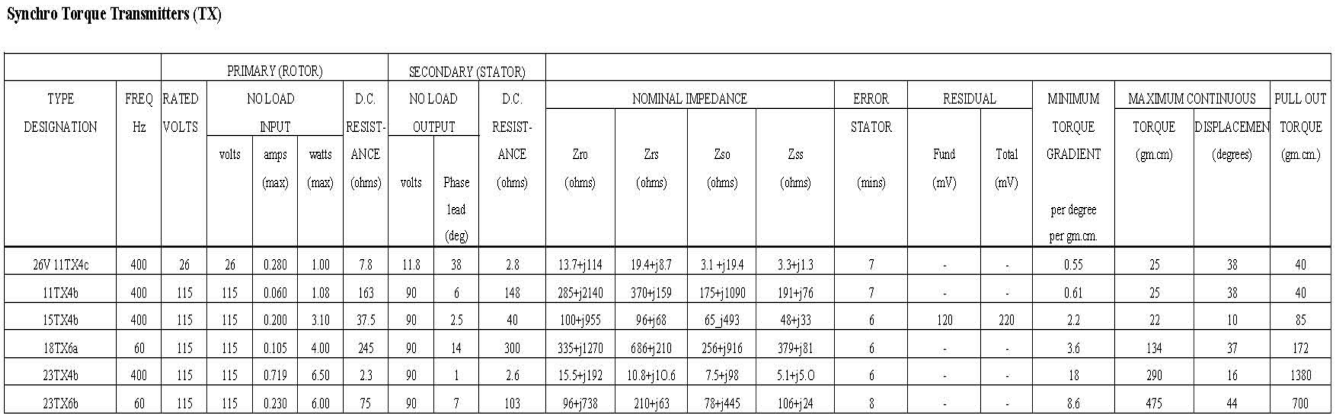
		PRIMARY (ROTOR)					SECONDARY (STATOR)										
TYPE DESIGNATION	FREQ Hz	RATED VOLTS	NO LOAD INPUT			D.C. RESIST-ANCE (ohms)	NO LOAD OUTPUT		VOLTAGE GRADIENT volts/deg	D.C. RESIST-ANCE (ohms)	NOMINAL IMPEDANCE				STATOR ERROR (mins)	RESIDUAL	
			volts	amps (max)	watts (max)		volts	Phase lead (deg)			Zro (ohms)	Zrs (ohms)	Zso (ohms)	Zss (ohms)		Fund (mV)	Total (mV)
26V 08CT4(B1)	400	11.8	10.2	0.137	0.47	28	22.5	13.5	0.39	145	173 +j564	253 +j104	25 +j93	-	10	30	60
26V 08CT4c	400	11.8	10.2	0.023	0.057	99	22.5	8.5	0.39	423	607+j2900	800+j300	100+j506	140+j53	7	25	30
26V 11CT4d	400	11.8	10.2	0.086	0.184	16.7	22.5	6.0	0.39	87	130 +j716	151 +j73.5	20+j128	27+j13.8	7	15	18
11CT4e	400	90	78	0.018	0.31	529	57.3	4.5	1.0	347	510+j3020	535+j302	700+j4900	900+j515	7	32	60
15CT4c	400	90	78	0.010	0.165	897	57.3	4.2	1.0	589	837 +j5170	943 +j589	1020+j8330	1500+j982	6	32	60
15CT6d	60	90	78	0.013	0.21	1300	57.3	9.5	1.0	900	970+j3800	1430+j409	1140+j6240	2280+j836	6	45	65
18CT4c	400	90	78	0.007	0.07	863	57.3	2.5	1.0	367	800+j7770	745 +j782	1360+j12600	1240+j1250	6	20	30
18CT6d	60	90	78	0.017	0.45	2140	57.3	18.0	1.0	1030	1050+j3280	1880+j611	1690+j4800	2830+j848	6	25	45
23CT4c	400	90	78	0.0057	0.071	730	57.3	2.0	1.0	330	750+j8570	660+j812	1230+j14300	1100+j1360	6	20	45
23CT6d	60	90	78	0.0185	0.5	1830	57.3	14.0	1.0	800	883+j3080	1500+j512	1380+j4790	2370+j791	6	30	45

FIG. A-1 COMMON SYNCHRO PARAMETERS.



Synchro Control Differential Transmitters (CDX)

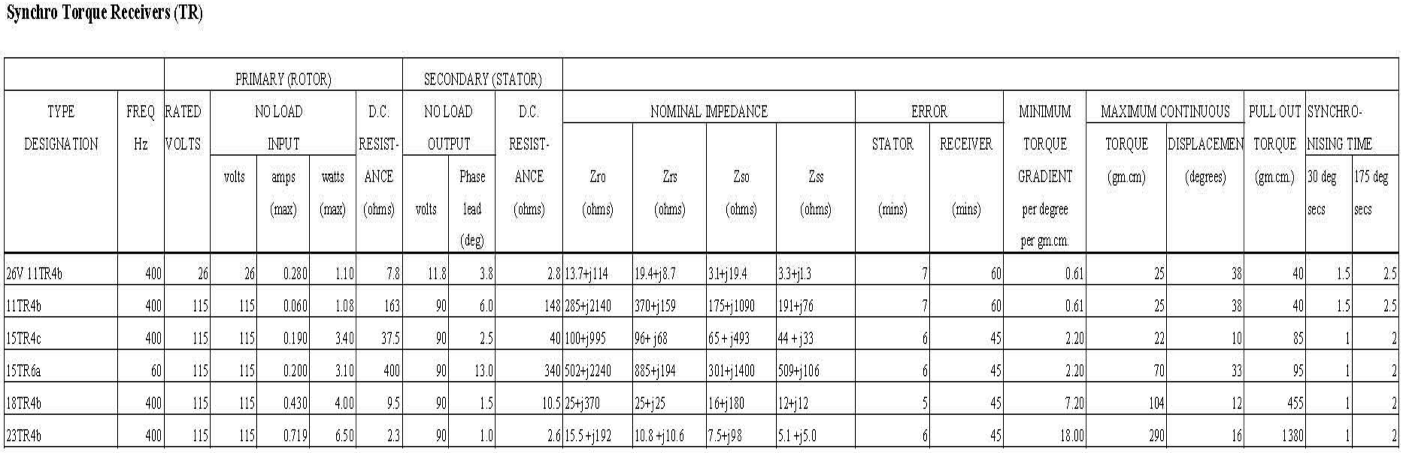
		PRIMARY (ROTOR)					SECONDARY (STATOR)										
TYPE DESIGNATION	FREQ Hz	RATED VOLTS	NO LOAD INPUT			D.C. RESIST-ANCE (ohms)	NO LOAD OUTPUT		D.C. RESIST-ANCE (ohms)	NOMINAL IMPEDANCE				ERROR		RESIDUAL	
			volts	amps (max)	watts (max)		volts	Phase lead (deg)		Zro (ohms)	Zrs (ohms)	Zso (ohms)	Zss (ohms)	STATOR (mins)	ROTOR (mins)	Fund (mV)	Total (mV)
26V 08CDX4(B1)	400	11.8	10.2	0.200	0.800	19	11.8	13.0	34	-	-	20+j56	-	10	10	30	60
26V O8CDX4c	400	11.8	10.2	0.108	0.300	24	11.8	9.5	36	33+j124	46+j14	24+j108	39+j14	7	7	20	30
26V 11CDX4c	400	11.8	10.2	0.150	0.340	10.6	11.8	5.7	16.6	17.6+j86	20.7+jS.7	12.2+j75	I7.5+j8.5	7	7	17	26
11CDX4b	400	90	78	0.049	0.730	191	90	4.7	446	450+j1930	487+j200	242+j1690	421+j211	7	7	60	90
15CDX4d	400	90	78	0.090	1.340	10	90	5.2	139	159+j1060	190+j125	129+j917	164+j111	6	6	32	60
15CDX6c	60	90	78	0.038	0.630	515	90	10.0	960	780+j2625	1114+j227O	435+j2270	930+j880	7	7	60	100
18CDX4c	400	90	78	0.128	1.210	47	90	3.0	46	65+j669	72+j71	63+j623	65+j64	6	6	40	75
18CDX6d	60	90	78	0.052	1.450	599	90	17.0	897	717+j1850	1130+j315	465+j1490	885+j308	7	7	60	100
23CDX4c	400	90	78	0.285	2.900	18	90	3.0	19	26+j310	27+j30	24+j280	24.7+j27.2	7	7	30	60
23CDX6c	60	90	78	0.090	1.820	255	90	11.0	315	-	453+j147	214+j947	-	8	8	40	65



Synchro Torque Transmitters (TX)

		PRIMARY (ROTOR)					SECONDARY (STATOR)													
TYPE DESIGNATION	FREQ Hz	RATED VOLTS	NO LOAD INPUT			D.C. RESIST-ANCE (ohms)	NO LOAD OUTPUT		D.C. RESIST-ANCE (ohms)	NOMINAL IMPEDANCE				ERROR	RESIDUAL		MINIMUM TORQUE GRADIENT per degree per gm.cm.	MAXIMUM CONTINUOUS		PULL OUT TORQUE (gm.cm.)
			volts	amps (max)	watts (max)		volts	Phase lead (deg)		Zro (ohms)	Zrs (ohms)	Zso (ohms)	Zss (ohms)	STATOR (mins)	Fund (mV)	Total (mV)		TORQUE (gm.cm)	DISPLACEMEN (degrees)	
26V 11TX4c	400	26	26	0.280	1.00	7.8	11.8	38	2.8	13.7+j114	19.4+j8.7	3.1 +j19.4	3.3+j1.3	7	-	-	0.55	25	38	40
11TX4b	400	115	115	0.060	1.08	163	90	6	148	285+j2140	370+j159	175+j1090	191+j76	7	-	-	0.61	25	38	40
15TX4b	400	115	115	0.200	3.10	37.5	90	2.5	40	100+j955	96+j68	65_j493	48+j33	6	120	220	2.2	22	10	85
18TX6a	60	115	115	0.105	4.00	245	90	14	300	335+j1270	686+j210	256+j916	379+j81	6	-	-	3.6	134	37	172
23TX4b	400	115	115	0.719	6.50	2.3	90	1	2.6	15.5+j192	10.8+j1O.6	7.5+j98	5.1+j5.O	6	-	-	18	290	16	1380
23TX6b	60	115	115	0.230	6.00	75	90	7	103	96+j738	210+j63	78+j445	106+j24	8	-	-	8.6	475	44	700

FIG. A-2 SYNCHRO CONTROL DIFFERENTIAL TRANSMITTERS AND SYNCHRO TORQUE TRANSMITTERS.



Synchro Torque Receivers (TR)

		PRIMARY (ROTOR)					SECONDARY (STATOR)														
TYPE DESIGNATION	FREQ Hz	RATED VOLTS	NO LOAD INPUT			D.C. RESIST-ANCE (ohms)	NO LOAD OUTPUT		D.C. RESIST-ANCE (ohms)	NOMINAL IMPEDANCE				ERROR		MINIMUM TORQUE GRADIENT per degree per gm.cm.	MAXIMUM CONTINUOUS		PULL OUT TORQUE (gm.cm.)	SYNCHRO-NISING TIME	
			volts	amps (max)	watts (max)		volts	Phase lead (deg)		Zro (ohms)	Zrs (ohms)	Zso (ohms)	Zss (ohms)	STATOR (mins)	RECEIVER (mins)		TORQUE (gm.cm)	DISPLACEMEN (degrees)		30 deg secs	175 deg secs
26V 11TR4b	400	26	26	0.280	1.10	7.8	11.8	3.8	2.8	13.7+j114	19.4+j8.7	3.1+j19.4	3.3+j1.3	7	60	0.61	25	38	40	1.5	2.5
11TR4b	400	115	115	0.060	1.08	163	90	6.0	148	285+j2140	370+j159	175+j1090	191+j76	7	60	0.61	25	38	40	1.5	2.5
15TR4c	400	115	115	0.190	3.40	37.5	90	2.5	40	100+j995	96+ j68	65 + j493	44 + j33	6	45	2.20	22	10	85	1	2
15TR6a	60	115	115	0.200	3.10	400	90	13.0	340	502+j2240	885+j194	301+j1400	509+j106	6	45	2.20	70	33	95	1	2
18TR4b	400	115	115	0.430	4.00	9.5	90	1.5	10.5	25+j370	25+j25	16+j180	12+j12	5	45	7.20	104	12	455	1	2
23TR4b	400	115	115	0.719	6.50	2.3	90	1.0	2.6	15.5 +j192	10.8 +j10.6	7.5+j98	5.1 +j5.0	6	45	18.00	290	16	1380	1	2

FIG. A-3 SYNCHRO TORQUE RECEIVERS.

Appendix C

HARMONIC DISTORTION OF THE REFERENCE WAVEFORM

Common Signal Distortion

Tracking type Synchro to Digital converters are not sensitive to distortion of the reference waveform, very large distortions like 20% third harmonic will have negligible effect on the working of the converters. Distortion of the reference will alter the internal loop gain of the converter, but since the type 2 servo loop is employed in all the tracking converters very large loop changes can be tolerated without errors being caused.

The following analysis shows the way in which distortion of the reference waveform is of no practical consequence.

If there is distortion on the reference the resolver form signals can be represented by:

$$\text{Sin}\,\phi \sum_{n=1}^{n=N} B_n\ \text{Sin.}(n\omega t + \alpha_n)$$

and

$$\text{Cos}\,\phi \sum_{n=1}^{n=N} B_n\ \text{Sin.}(n\omega t + \alpha_n)$$

where ϕ, is the resolver angle, $\omega = 2\pi f$, where f is the reference fundamental frequency with B_n and α_n as the harmonic amplitudes and phases.

The operation of the tracking control loop is to multiply the resolver form signals by Cos θ and Sin θ respectively, where θ is the RDC output angle. They are then subtracted and the result is applied to a phase sensitive detector to produce the control loop error signal. The error signal is reduced to zero by the action of the control loop. Carrying out these operations in steps we have:

$$\varepsilon_1 = \text{Sin}\,\phi \sum_{n=1}^{n=N} B_n\ \text{Sin.}(n\omega t + \alpha_n).(\text{Sin}\,\phi.\text{Cos}\,\theta - \text{Cos}\,\phi.\text{Sin}\,\theta)$$

$$\varepsilon_1 = \text{Sin}\,\phi \sum_{n=1}^{n=N} B_n\ \text{Sin.}(n\omega t + \alpha_n).(\text{Sin}\,\phi - \theta)$$

where ε_1 is the error signal before the phase sensitive detector.
Then:

$$\varepsilon_1 = \text{Sin}\,\phi \sum_{n=1}^{n=N} B_n \ \text{Sin}.(n\omega t + \alpha_n).(\text{Sin}\,\phi - \theta)$$

where ε is the error after the phase sensitive detector and integrator.
The summation part of the above equation i.e.

$$\sum_{n=1}^{n=N} B_n \int_{\omega=0}^{\omega=\pi} \text{Sin}.(n\omega t + \alpha_n).\,dt$$

is just a constant, it will change in value according to the harmonic content but the important point is that this gives rise only to a change of loop gain and for the type 2 loop no errors will be caused by very large changes in this factor.

Differential Distortion

While distortion of the reference waveform is of little consequence, since it occurs on *both* the sine and cosine channels, distortion of one channel only has a very different effect. In practice there is no reason why the carrier on the sine channel should be distorted differently from that of the cosine channel. It could be that amplifiers giving distortion are being used in which case it is worth knowing the effect of the differential distortion. Differential distortion does produce errors.
The following simple analysis shows the effect of 1% third harmonic (in phase with the carrier at 0^0) added to the sine input with the cosine input undistorted.
Let the input signal be:

$\text{Sin}\ \omega t\ \text{Sin}\ \phi + K\ \text{Sin}\ 3\omega t\ \ \text{Sin}\ \phi$ (Sine input)
$\text{Sin}\ \omega t\ \text{Cos}\ \phi$ (Cosine input)

As before the operation of the converter is to multiply the sine input by Cos θ and to multiply the cosine input by Sin θ to subtract them, pass them through a phase sensitive detector and integrate the output to produce the error signal. Fig. C-1 shows the system and the equations for the voltages at the different points.

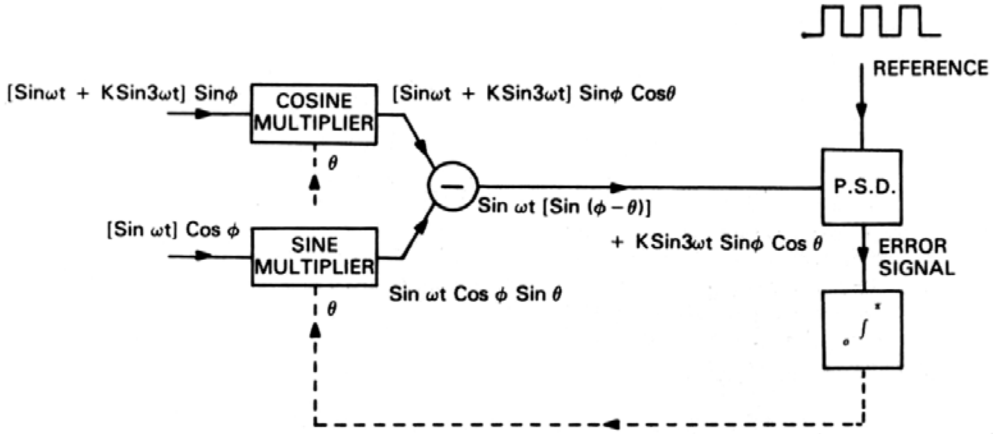


FIG. C-1 THE EFFECT OF DIFFERENTIAL DISTORTION ON SINE CHANNEL ONLY.

(1) Assume $\theta \approx \phi$ due to the feedback.

(2) The error is caused by the second term of the output from the subtractor and for $\theta \approx \phi$, $\mathrm{Sin}\phi \ \mathrm{Cos}\theta$ has a maximum of 0.5 for $\theta \approx \phi = 45°$.

(3) For $\theta \approx \phi = 45°$. the signal into the PSD is:

$$\mathrm{Sin}\ \omega t\ [\mathrm{Sin}\ (\theta - \phi)] + 0.5\ K\ \mathrm{Sin}\ 3\omega t$$

(4) The output from the PSD is integrated and reduced to zero by the control loop.

(5) To simulate the effect of the PSD, integration is carried out only over one half period of the carrier. Due to the phase reversal of the PSD the other half period will be the same.

Writing $$\phi - \theta = \varepsilon$$

$$\mathrm{Sin}\ \varepsilon \int_0^{\pi} \sin \omega t\ d\omega t + 0.5K \int_0^{\theta} \mathrm{Sin}\ 3\omega t\ d\omega t = 0$$

or

$$\mathrm{Sin}\ \varepsilon\ [\mathrm{Cos}\ \omega t]_{\omega t = 0}^{\omega t = \pi} + 0.5K\ [{}^{1}/_{2}\ \mathrm{Cos}\ 3\omega t]_{\omega t = 0}^{\omega t = \pi} = 0$$

which gives:

$$2\ \mathrm{Sin}\ \varepsilon + K/3 = 0$$

and for ε in radians and ε small

$$\varepsilon = -\ K/6$$

For example if $K = 0.01$ (1 % third harmonic)

$$\varepsilon^{0} = 0.01/6 \times 57 = 0.095°$$

The conclusion here then is that differential harmonic distortion does have a considerable effect on the accuracy of the converter. Fortunately the areas where it is likely to occur are within the converters themselves, and care has been taken in the design to avoid errors due to this cause.

Appendix F

EFFECTS OF QUADRATURE SIGNALS ON SERVO SYSTEMS

The usual arrangement of the Digital to Synchro converter in a control loop is shown in Chapter 4, Fig. 4-38. The signal from the control transformer is amplified and fed into a Phase sensitive detector (PSD). The DC output from the PSD forms the error signal for the control loop.

As can be seen from Fig. 4-38, the PSD is driven from the reference signal and the operation of the PSD is such as to give a gain of + 1 when the reference is positive and a gain of -1 when the reference signal is negative. Simple consideration of the PSD will show that, if an AC voltage at the same frequency as the reference voltage but shifted in phase by 90 degrees is introduced in series with the usual input from the CT, no errors will be caused. (Errors could however be caused by the injection of such an AC voltage, if the voltage was of sufficient magnitude to cause asymmetric limiting in the amplifiers). Such an injection of a 90^0 phase shifted signal *is not the same* as the introduction of a real quadrature voltage caused by different phase shifts in the signal paths.

The following simple analysis shows the errors due to quadrature and how these errors are increased by a signal to reference phase shift. The signals will be considered in Resolver form to reduce the number of terms in the equations.

Referring to Fig. F-1, we will consider the reference to be in phase with the input signals and then introduce a small phase shift on one signal relative to the other.

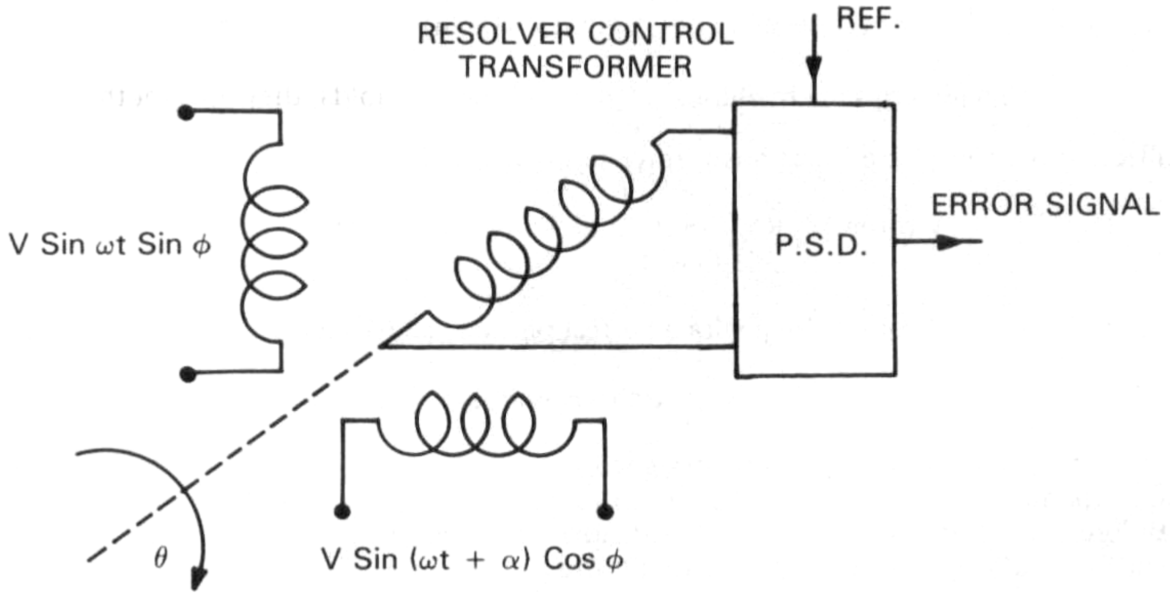


FIG. F-1 A RESOLVER WITH A DIFFERENTIAL SIGNAL PHASE SHIFT A.

In a perfect system the voltages would be,

$$Vs = V\sin\omega t.Sin\phi$$
$$Vc = V\sin\omega t.Cos\phi$$
$$V = V\sin\omega t$$

To show how the quadrature terms arises a phase shift of a will be applied to the carrier in Ye. The three voltages are now:

$$Vs = V\sin\omega t.Sin\phi$$
$$Vc = V\sin(\omega t+\alpha).Cos\phi$$
$$V = V\sin\omega t$$

At a fixed angle θ the Resolver behaves like two transformers with a common secondary where the ratios are:

$R\ Cos\ \theta \rightarrow$ Sine input to rotor
and - $R\ Sin\ \theta \rightarrow$ Cosine input to rotor

The equivalent R for the Synchro control transformer type 11CT4L, (9Ov L-L) is 0.64.
The voltage in the rotor winding will be the sum of the two voltages i.e.

$$Vrotor = (VSin\omega t.sin\phi)\ R\ Cos\ \theta - [Vsin\ (\omega t + \alpha)\ Cos\ \phi]\ R\ Sin\ \theta \quad (1)$$

Where ϕ is the digital angle and θ is the angle of the resolver shaft and a is the phase shift introduced into the Cosine channel.

In equation (1) the next step is to expand the term

$$Sin\ (\omega t + \alpha)$$

by using the relationship:

$$\text{Sin (A + B) = Sin A Cos B + Cos A Sin B}$$

Doing this we get,

$$V\ rotor = RV[\sin\omega t^{*}.\ \sin\phi.\ \cos\theta - \cos\phi.\ \sin\theta\ (\sin\omega t.\cos\alpha + \cos\omega t\ ^{**}\sin\alpha)]$$

*These terms are in phase. ** This is the quadrature term.

Collecting the "in-phase" and quadrature terms we have:

$$V\ rotor = RV[Sin\omega t\ (Sin\phi.Cos\ \theta - Cos\phi.Sin\theta.Cos\alpha) \quad \ldots(2)$$
$$+ Cos\omega t(Cos\phi.Sin\theta.Sin\alpha)]$$

A properly designed control loop with a perfect phase sensitive detector will ignore the term:

$$Cos\omega t(Cos\phi.Sin\theta.Sin\alpha)$$

in equation (2). For such a properly designed servo loop there is an error which is very small due to the fact that Cos α in the first term of equation (2) is not quite equal to 1.

Before proceeding to the case of the quadrature term itself we will find what the error would be in a loop which rejects the quadrature.

We make use of the fact that

$$Cos\alpha = 1 + \frac{\alpha^2}{2} + \frac{\alpha^4}{4!} \ldots\ldots\ldots\ldots\ (\alpha \text{ in radians})$$

and for small α (which we are considering)

$$Cos\alpha = 1 - \frac{\alpha^2}{2} \quad \text{where } \alpha \text{ is in radians.}$$

Since we are concerned for the present with a good loop which rejects the quadrature signal, we can ignore that term in the error signal. Doing this and substituting for $Cos\ \alpha$ as above gives:

$$Vrotor = RV\{Sin\omega t.[Sin\phi.Cos\theta - (1 - \alpha^2/2)\ Sin\ \theta.Cos\ \phi]\}$$

The servo will alter θ to make $Vrotor = zero$.

i.e. $$0 = [Sin\phi.Cos\theta - Sin\theta.Cos\phi + \alpha^2/2\ Sin\ \theta.Cos\ \phi] \qquad (3)$$

In equation (3), it is the term

$$\frac{\alpha^2}{2}\ Sin\ \theta.\ Cos\ \phi$$

which gives rise to the error.

For $\phi \approx \theta$, $Sin\theta.\ Cos\ \phi$ has a maximum of 0.5 at $\theta \approx 45^0$

And since $Sin\ \phi\,Cos\ \theta - Sin\ \theta\,Cos\ \phi \cong (\phi - \theta)$ radians, the error in radians is:

$$\varepsilon = \frac{\alpha^2}{2} \times 0.5 \text{ (}\alpha\text{ and error are in radians)}$$

$$\text{error in degrees} = \frac{\alpha^2 \times 0.5}{57 \times 2} \text{ (}\alpha\text{ in degrees).}$$

$$\text{error in minutes} = \frac{60 \times 0.5\alpha^2}{57 \times 2} \quad \text{(}\alpha\text{ in degrees}$$

$$\approx \frac{\alpha^2}{4} \qquad \text{(}\alpha\text{ in degrees).}$$

i.e. ¼ arc minute for 10 of phase at worst angle of 45^0

We now look at the quadrature signal which should be rejected. It is the term

$RV\ Cos\ \omega t\ [Cos\ \phi\ sin\ \theta\ Sin\ \alpha]$ of equation (2)

For $\phi \approx \theta$, the maximum $Cos\ \phi\ Sin\ \theta$ is for $\phi \approx \theta = 45^0$ and the value is 0.5.

The peak value of the quadrature is

Quadrature = α RV x 0.5 (α is in radians) ($Sin\ \alpha \approx \alpha$)
$V = 90\sqrt{2}$
R = 0.64 for the 11CT4b Control Transformer (90 volts L-L)
and for $\alpha = 1/57$ (1 degree).

The rms value of the quadrature on the rotor is $\dfrac{90 \times 0.64 \times 0.5}{57}$ volts per degree.

rms Quadrature Voltage on rotor = 0.5 volts per 1 degree of differential phase shift.

i.e. For l00mV rms the differential phase has to be 0.2 degrees.

The foregoing example of the effect of quadrature was based on the assumption that the signals and reference were in phase before the small differential phase shift was introduced. In practical systems there is often a phase shift of several degrees between the signals and reference. This phase shift should be minimised in the design of Synchro systems. Both control transmitter and control receiver Synchros give rise to phase leads between the input and output voltages and balancing phase leads are often introduced into the reference before it is used to drive the phase sensitive detector. DSC’s generally give negligible phase shift between the input reference and output signals, if therefore a CX is replace by a DSC, the phase angle between the CT output voltage and the reference will be changed and a corresponding correction should be put in to the system at some point.

The following simple analysis shows the effects of quadrature signals in the presence of signal to reference phase shift. Again to reduce the number of terms in the equations the resolver example will be considered.

The effect of reference to signal phase shift with quadrature

Let the resolver form signals be:

$$Sin\ \omega t\ Cos\ \phi \text{ and } Sin\ (\omega t + \alpha)\ Sin\ \phi$$

The control resolver rotor voltage will be:

$$Sin\omega t.\ Cos\ \phi.Sin\theta - Sin\ (\omega t + \alpha).Sin\ \phi.\ Cos\ \theta$$

where θ is the shaft angle.

The action of the phase sensitive detector with a phase shifted reference where the phase shift is β is given by integrating the resolver rotor output with respect to ωt from $\omega t = \beta$ to $\omega t = \beta + \pi$. The control loop will set the result to zero i.e.:

$$Cos\phi.Sin\theta\int_{\beta}^{\beta+\pi} Sin\omega t.d\omega t - Sin\phi.Cos\theta\int_{\beta}^{\beta+\pi} Sin\omega t.d\omega t = 0$$

Expanding $Sin\ (\omega t + \alpha)$ and integrating gives:

$$Cos2.Sin3.[Coswt].{}_{\omega t=\beta}^{\omega t=\beta+\pi} + Sin\phi.Cos\theta.Cos\alpha.[Cos\omega t]_{\omega t=\beta}^{\omega t=\beta+\alpha} - Sin\phi.Cos\theta.[Sin\omega t]_{\omega t=\beta}^{\omega t=\beta+\pi} = 0$$

or

$$-2.Cos\phi.\ Sin\theta\ Cos\beta + 2Sin\phi\ Cos\theta.Cos\alpha.Cos\beta - 2Sin\phi.Cos\theta.Sin\alpha\ Sin\beta = 0$$

Now both β and α are small so:

$$Cos\alpha \approx 1 - \frac{\alpha^2}{2} \text{ and } Sin\ \beta \approx \beta \text{ may be used.}$$

where α and β are in radians.

Making these substitutions and rearranging the terms gives:

$$\left(1 - \frac{\beta^2}{2}\right).Sin(\phi - \theta) - \left(1 - \frac{\beta^2}{2}\right)\frac{\alpha^2}{2}.Sin\phi.Cos\theta - \alpha\beta.Sin\phi.Cos\theta = 0$$

The second and third terms in this expression are the ones which cause the error. The coefficients Sinϕ , Cos θ which occur in both these terms have a maximum value of 0.5 for $\phi \approx \theta$. Substituting 0.5 for Sinϕ , Cos θ to give the maximum error (which is for $\theta \approx \phi$ = 45 degrees) gives:

$$\left(1 - \frac{\beta^2}{2}\right).Sin(\phi - \theta) - 0.5[\left(1 - \frac{\beta^2}{2}\right)\frac{\alpha^2}{2}. + \alpha\beta] = 0$$

And this formula can be used to calculate the error, as an example for

$$\alpha = \frac{1}{57} \text{ and } \beta = \frac{5}{57}$$

i.e. 1 degree differential phase shift (which is large) and +5 degrees phase shift on the reference.

The error is very nearly equal to:

$0.5\ \alpha\beta$ radians

or $\frac{0.5 \times 5}{57 \times 57}$ radians, for 1^0 differential and 5^0 reference phase shift.

or $\frac{0.5 \times 5}{57}$ degrees

or $\frac{0.5 \times 5 \times 60}{57}$ arc minutes

or $\approx 0.5 \times 5 = 2.5$ arc minutes

This figure compares with the earlier figure of ¼ arc minute for the case with no reference phase shift.

It should be understood that the 1^0 differential phase shift taken in these examples is very large. Quadrature voltages in converters and CTs jointly is more likely to correspond to an equivalent phase shift of 0.2 degrees or less, i.e. the quadrature due to both the DRC and resolver will be less than 100 millivolts.