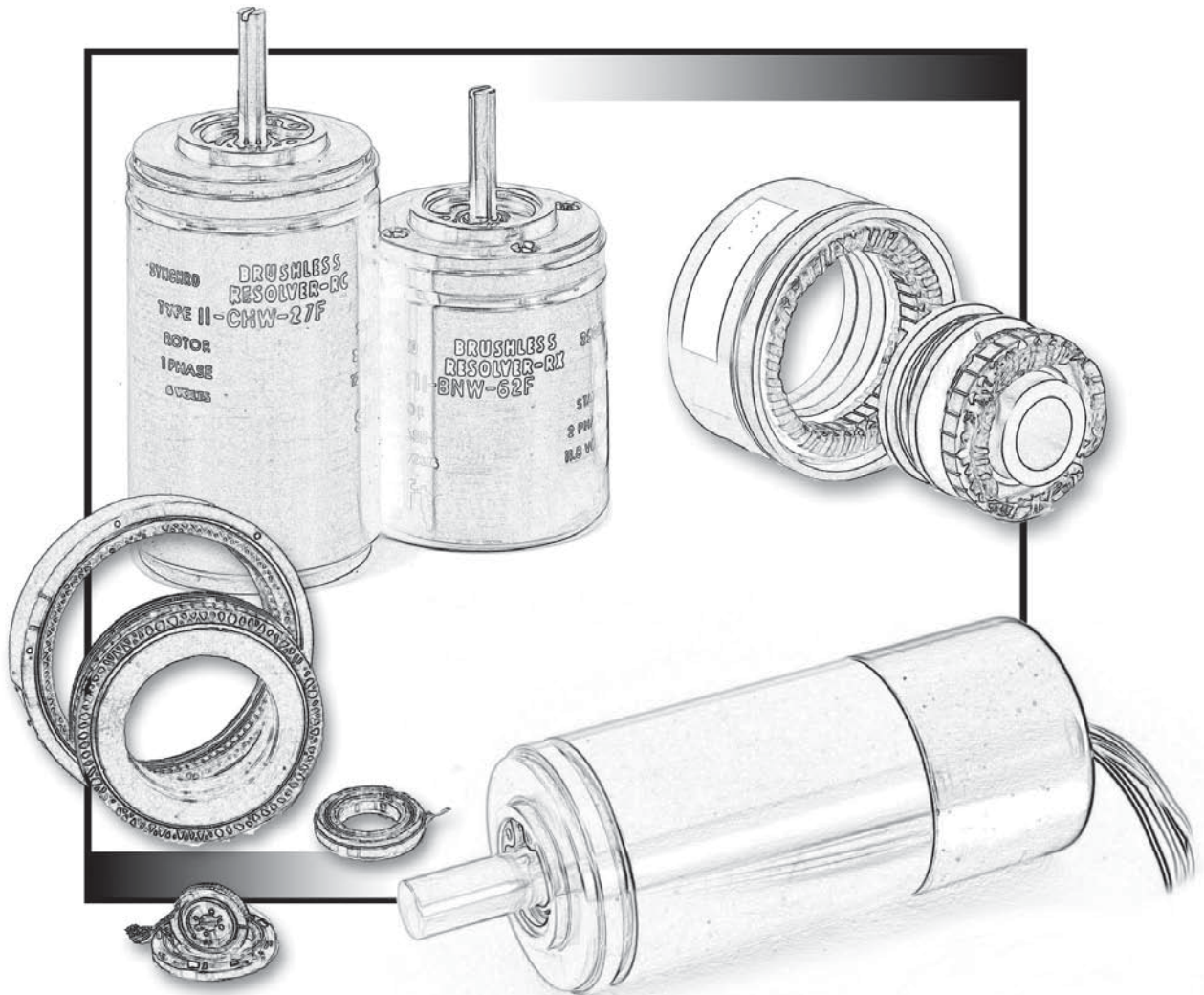


Synchro and Resolver Engineering Handbook



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1.0 Introduction

Synchros and resolvers have performed as part of electromechanical servo and shaft angle positioning systems for over 50 years. With experience, the market place has come to realize that, in conjunction with appropriate interface electronics, a synchro or resolver can form the heart of an outstanding digital shaft angle measurement and positioning system. The technology has been developed and the systems based on it are unsurpassed in reliability and cost effectiveness.

This handbook was written by the Moog Components Group engineering staff, inspired by questions from engineers working in the most sophisticated military and space programs. Many of our products were originally designed as state-of-the-art units. Some have since become standards. The engineering expertise of Moog Components Group is apparent in our participation in all manned spaced missions, many strategic missile programs, and our reputation in the industry.

For five decades, Moog Components Group has also been involved in the design, development, and production of rotating components for commercial, industrial and medical applications. Our synchros and

resolvers include conventional and pancake designs. These can be provided as brushless and/or multispeed units. Moog Components Group is also a leading manufacturer of brush and brushless DC motors. Our machine shops contain modern equipment to produce precision components for bar and strip stock. Our in-house capability for making lamination dies enables us to quickly change the number of slots and inside and/or outside diameters, to suit virtually any design requirement.

The components described in this handbook are just a small selection from a broad spectrum of devices that we manufacture. Dedicated people, with years of experience in manufacturing products with high standards, staff all of our facilities.

We maintain a network of sales offices across the United States and Internationally. Our staff engineers are available to support your design efforts or to work as part of your proposal team.

We look forward to working with you to meet your component requirements.



2.0 Synchros and Resolvers

2.1 Theory of Operation and Classic Applications

A synchro functions as an electromechanical transducer which, as a circuit element, is essentially a variable coupling transformer. The magnitude of the magnetic coupling between the primary and secondary varies according to the position of the rotating element. This in turn varies the magnitude of the output voltage. In some systems, a mechanical input, such as a shaft rotation, is converted to a unique set of output voltages. In others, a set of input voltages is used to turn a synchro rotor to a desired position.

Synchros can be classified in two overlapping groups: torque synchros and control synchros.

Torque synchros include transmitters (CG), differentials (CD) and receivers (CR).

Control synchros include transmitters (CG), differentials (CD) control transformers (CT), resolvers (CS), linear transformers (LT) and the two hybrid units: transolvers (CSD) and differential resolvers (CDS).

2.1.1 Transmitter

The synchro transmitter (CG) consists of a single-phase, salient-pole (dumbbell-shaped) rotor and three-phase, Y-connected stator. (In this discussion, the word “phase” will always identify a space relationship unless a timephase relationship is specifically indicated.)

The primary or input winding is usually the rotor, with the stator as the secondary or output element. The rotor is excited through a pair of slip rings with an AC voltage. The field produced by this voltage induces a voltage into each of the stator phases. The magnitude of the induced voltage depends on the angle between the rotor fields and the resultant axis of the coils forming that stator phase. Since the axes of the three stator phases are 120° apart, the magnitudes of the stator output voltages can be written as:

$$V_{S1-3} = KVR_{2-1} \sin \theta$$

$$V_{S3-2} = KVR_{2-1} \sin (\theta + 120^\circ)$$

$$V_{S2-1} = KVR_{2-1} \sin (\theta + 240^\circ)$$

where K is the maximum coupling transformation ratio (TR), which is defined as $TR = \frac{V_{out(max)}}{V_{in}}$ and is a scalar quantity.

θ is the rotor position angle. V_{S1-3} is the voltage from the S1 terminal to the S3 terminal. All other voltages are similarly defined throughout this discussion.

These stator voltages are either approximately in time phase or 180° out of time-phase with the applied voltage. The amount by which the output voltages differ from an exact 0° or 180° time-phase relationship with the input voltage is known as the synchro (time) phase shift.

For a synchro operating at 400 Hz working into an open circuit, the output voltage will always lead the input voltage by a few degrees (8 to 20° for small sizes; 2 to 8° for larger sizes).

The transmitter equations show that no where over the entire 360° rotation of the rotor will the same set of stator voltages appear. The transmitter, therefore, supplies information about the rotor position angle as a set of three output voltages. To convert this information, it is necessary to use an instrument which will measure the magnitude of these voltages, examine their time-phase relationships, and return them to their original form: a shaft position. Such a device is the synchro receiver (CR). These two units form the most basic synchro system.

2.1.2 Receiver

The construction of the receiver is electrically identical to that of the transmitter. The output voltages vary with rotor position in the same manner as those of the transmitter. In use, the receiver is connected back-to-back with a transmitter. Like-numbered terminals are connected together (see Figure 2.1.2) and the rotors are excited in parallel. At the instant the system is energized, voltage differences exist across each pair of stator windings if the rotors of the units are not at the exact same angle relative to the stator phases. This causes current to flow in both stators, producing a torque on each rotor.

Since the transmitter rotor is constrained, the resultant torque acts on the receiver rotor in such a direction as to align itself with the transmitter. When alignment occurs, the voltages at each stator terminal are equal and opposite, and no current flows. Perfect synchronization is never achieved in practice because of the internal friction (due to bearings and brushes) of the receivers. To minimize this error, the receiver is designed to have a very low starting friction, usually less than 2700 mg-mm.

Turning the transmitter rotor from the equilibrium position will again exert a force on the receiver rotor. As soon as this developed force exceeds the receiver's internal friction, the receiver will track the transmitter to its new position. The torque developed on the receiver shaft is proportional to the angle between the two rotors and is usually expressed in mg-mm/deg. Methods of measuring the torque produced by a transmitter-receiver pair can be found in the *Society of Automotive Engineers Specification ARP-461B*.

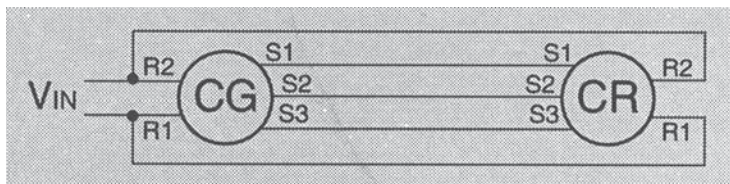


Figure 2.1.2

Receivers are constructed to minimize oscillation, overshoot, and spinning when the rotor is turning to a new position. The time required for the rotor to reach and stabilize at its new rest position is called the damping or synchronizing time. This time varies with the size of the receiver, the inertia of the load, and the system torque.

This type of basic system is used to transmit angular information from one point to another without mechanical linkages. The standard transmission accuracy for such a system is 30 arc minutes. Information can be sent to several locations by paralleling more than one receiver across a transmitter. Multiple receivers decrease the accuracy of the system and increase the power draw from the source.

2.1.3 Differential

The differential (CD) is another type of synchro that may be added to the basic torque system. The differential stator has a three-phase, Y-connected winding and is usually the primary element. The rotor is cylindrical and

is also wound with three Y-connected phases. The output voltages of the differential depend not only on the input voltages but also on the rotor shaft position. As shown in Figure 2.1.3(a) the differential stator is normally excited from the transmitter stator, and the differential rotor is connected to the receiver stator. The output voltages of the differential are now dependent on both the transmitter rotor position θ_{CG} and its own rotor position θ_{CD} . The receiver rotor will seek a position θ_{CR} , where $\theta_{CR} = \theta_{CG} \pm \theta_{CD}$, depending on how the CG and CD stators are interconnected.

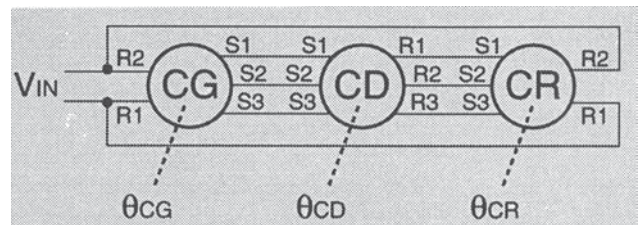


Figure 2.1.3(a)

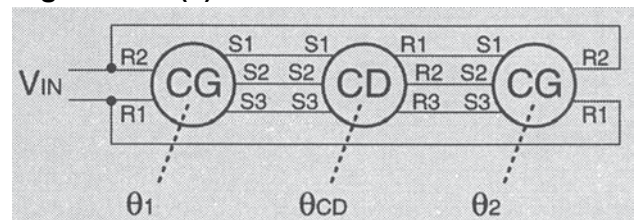


Figure 2.1.3(b)

The differential may also be positioned between two transmitters as shown in Figure 2.1.3(b). As each transmitter is turned to its desired angle, the differential rotor is forced to assume a position which is either the sum or the difference of the angles between the transmitter rotors ($\theta_{CD} = \theta_1 \pm \theta_2$). In this application, the differential is sometimes called a differential receiver and is constructed to have a low starting friction (5000 mg-mm) to minimize system errors. An accuracy of one degree is standard.

Unit torque gradients are typically 3000 mg-mm per degree of receiver displacement. This is sufficient to turn a dial or a pointer but nothing larger without increasing system errors. For large torques, synchros are used to control other devices which will provide the necessary torque levels. An integral part of these control systems is the synchro control transformer (CT).

2.1.4 Control Transformer

The control transformer consists of a three-phase, Y-connected stator and a single-phase cylindrical drum rotor. In normal usage, with the stator as the primary element, the unit is connected as shown in Figure 2.1.4(a). As the transmitter rotor turns (with the control transformer rotor stationary) the magnitude of the control transformer stator field remains constant. Its direction matches that of the transmitter. The field cutting across the control transformer rotor induces a voltage in the rotor. The magnitude of this voltage depends on the sine of the angle between the axis of the rotor winding and the stator flux vector. Since the angle of the flux field depends upon the transmitter rotor angle, the control transformer output voltage provides information about the transmitter rotor position.

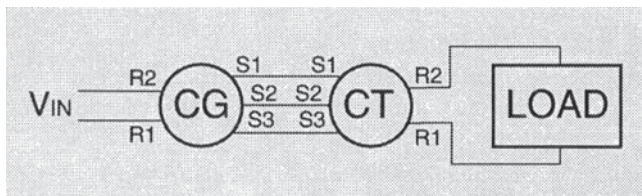


Figure 2.1.4(a)

If the control transformer rotor angle is not the same as that of the transmitter, a voltage proportional to the sine of the angular difference appears on the control transformer rotor. This voltage is applied to a servo amplifier connected to the control phase of a servomotor. The motor, which is geared to the control transformer rotor shaft, will rotate until the rotor is at the same angle as the transmitter rotor. At this position, the control transformer output voltage is theoretically zero and motion will cease. With additional gearing, the servomotor provides a mechanical output for other useful work. This synchro system, which develops no torque of its own, acts as the control device for the motor which moves high torque loads. The accuracy of the entire system depends on the synchro error, amplifier gain, servo response, and gearing error. Using standard components, system error is usually specified as 10 arc minutes maximum. If multi-speed pancake synchros are used, accuracies in arc seconds are obtainable. This basic control system is shown below.

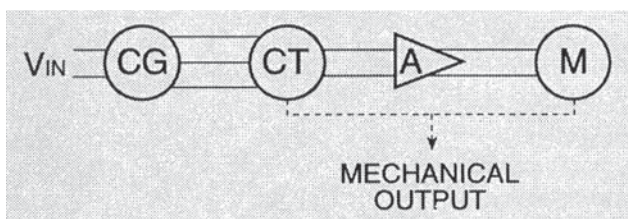
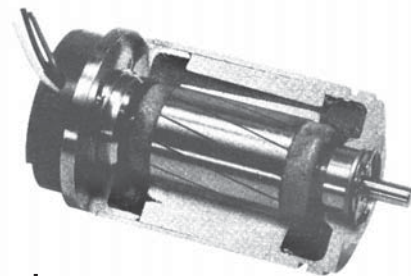


Figure 2.1.4(b)

2.1.5 Transolver and Differential Resolver

The transolver (CSD) is essentially a control transformer with a second rotor winding wound in space quadrature to the main winding. When used as a control transformer, the transolver's second rotor winding is dummy-loaded symmetrically with the main winding to avoid unbalances. When using the transolver as a transmitter, the unused rotor winding is shorted to ground. This provides electrical saliency and permits the transolver to operate as a transmitter without introducing additional errors. The differential resolver (CDS) is the inverse of the transolver. The rotor is the three-phase element and the stator the two phase element. In function, the transolver and the differential resolver are identical. Both find considerable use converting three-wire data to four-wire data. These units form the bridge between the three-phase devices (transmitters, receivers, differentials, and control transformers) and the two-phase devices (resolvers).



2.1.6 Resolver

The resolver (CS) consists of a cylindrical rotor with each of the two phases of the rotor and stator in space quadrature. The function of a resolver is to resolve a vector into its components. Energizing one phase of the input element, either rotor or stator, with a voltage (V) induces a voltage into the output windings. The magnitude of the output voltage varies with the sine and the cosine of the rotor position angle θ . The two outputs are $V \sin \theta$ and $V \cos \theta$ (assuming a unity transformation ratio), which are the components of the input vector V .

The vector resolution function is reversible. In operation, two voltages, X and Y , are applied to the inputs of the resolver and one output phase is nulled. The rotor position then indicates the vector angle θ equal to the arctan (X/Y). The other output phase, which is at maximum coupling, indicates the magnitude of the vector R equal to $\sqrt{X^2 + Y^2}$.

Exciting one input of a resolver with voltage A produces outputs of $A \sin \theta$ and $A \cos \theta$. Exciting the other input with voltage B produces outputs of $B \sin (\theta + 90)$ or $B \cos \theta$ and $B \cos (\theta + 90)$ or $-B \sin \theta$. Energizing both windings at once therefore results in two outputs, Y and X, whose magnitudes are of the form:

$$Y = A \sin \theta + B \cos \theta$$

$$X = A \cos \theta - B \sin \theta$$

Analytic geometry demonstrates that these two equations represent a transformation of axes by rotation without translation. Y and X are the new components obtained by rotating A and B through the angle θ .

Resolvers can be used wherever the transformation of coordinates from one system to another is desired. Space-craft and aircraft usually require the craft's pitch, roll, and yaw to be transformed back to earth references. One resolver is needed for two-axis transformation, while three are needed for three axes.

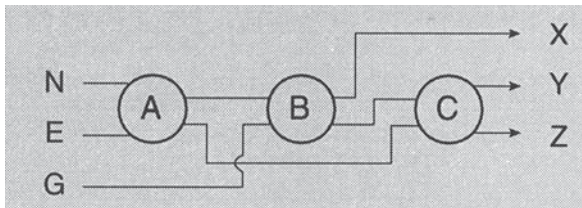


Figure 2.1.6(a)

Figure 2.1.6(a) schematically represents the interconnections of three resolvers necessary to transform from inertial platform coordinates (N, E, G) to an airborne vehicle's coordinates (X, Y, Z). This resolver chain essentially solves the matrix equation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos C & \sin C \\ 0 & -\sin C & \cos C \end{bmatrix} \begin{bmatrix} \cos B & 0 & \sin B \\ 0 & 1 & 0 \\ -\sin B & 0 & \cos B \end{bmatrix} \begin{bmatrix} \cos A & \sin A & 0 \\ -\sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} N \\ E \\ G \end{bmatrix}$$

Resolver chains are commonly used to solve trigonometric problems of varying degrees of complexity. Computing resolver amplifier chains are a combination of precision computing resolvers and amplifiers. The resolvers in this application are specifically designed to work with a buffer, booster, or feedback amplifier. They are known as feedback or compensated resolvers (CQ or CY).

The rotor of a compensated resolver, as shown in Figure 2.1.6.(b), is identical to that of a standard resolver. The stator, however, has two additional sets of coils, called the compensator or feedback

windings. The compensator winding is laid in the same slots as the stator winding.

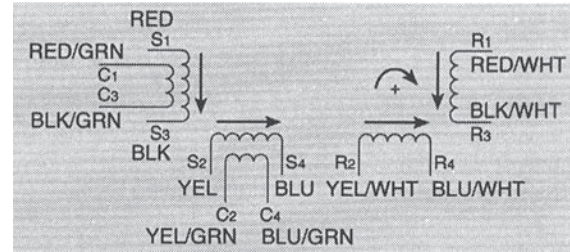


Figure 2.1.6(b)

Practically all the flux generated by the stator input current links all the turns of the compensator. Therefore the compensator output is essentially equal to the input voltage, and is constant with rotor position. The stator flux field induces both the output voltage of the compensator and the rotor output voltage. Therefore the time phase shifts of the two voltages are identical. Because of the resolver's construction, any change in the stator flux due to temperature or voltage, immediately produces a change in the compensator voltage. The negative feedback through the amplifier restores the stator field to its original conditions. A resolver-amplifier pair as shown in Figure 2.1.6(c) is therefore basically error free, with respect to resolver chain performance, over a wide range of environmental conditions.

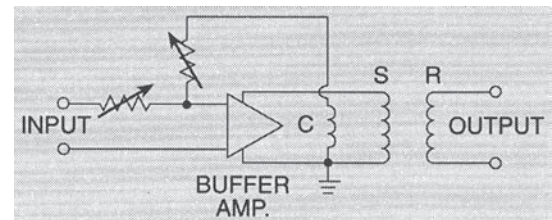


Figure 2.1.6(c)

Resolvers are also used in time-phase-shifting applications. A typical connection for a resolver phase shifter is shown in Figure 2.1.6(d). The resistance R is chosen to match the reactance of the capacitor C at the operating frequency. Both R and X_c are substantially higher than the resolver output short circuit impedance. Under proper operating conditions, the phase shifter output is:

$$V_{OUT} = K V_{IN} \angle \theta$$

Where K is the transformation ratio and θ is the rotor angle.

Note that the output voltage is constant with rotor position. However, the time-phase shift in electrical degrees between the output and the input is equal to the rotor position angle in

mechanical degrees. Using a balanced R-C network and a stable frequency source, standard resolvers can be used as phase shifters with an accuracy of $+0.25^\circ$ or better.

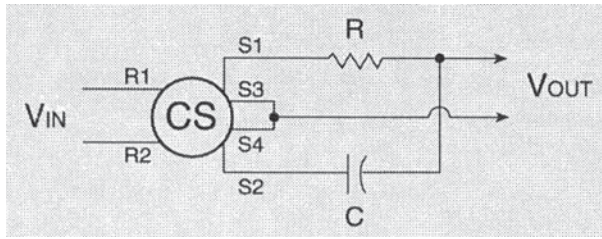


Figure 2.1.6(d)

Resolvers are also used in control systems exactly like those described for three-phase units. In these applications, the units are sometimes referred to as resolver transmitters, resolver differentials, or resolver control transformers.

2.1.7 Linear Transformer

A linear transformer (LT) consists of a one-phase, salient pole rotor and a single-phase stator. In all other synchros, the output voltage is proportional to the sine of the rotor position angle. But the linear transformer is constructed so that the output voltage is directly proportional to the angle itself. In equation form:

$$V_{OUT} = K\theta \quad (-50^\circ < \theta < +50^\circ)$$

The angular band over which the output equation remains valid is known as the excursion range. Beyond the excursion range, the plot of output voltage against rotor position tends toward a sinusoid. The linear transformer acts as a circuit replacement for a potentiometer with the chief advantages of low starting friction and infinite resolution over the excursion range. Because of construction similarities, the LT also matches the performance of resolvers over a wide range of environmental service conditions.

2.2 Brushless Synchros and Resolvers

For applications where conventional commutation with slip rings and brushes is either undesirable or unwanted, several varieties of brushless synchros, for either full or limited rotation, are available.

2.2.1 Electromagnetic Type

In the electromagnetic brushless synchro, energy is transferred from/to the rotor by means of a circular rotary transformer mounted in tandem with the synchro or resolver. Since there are no physical connections to the rotor, the life of the unit is limited solely by the life of the bearings. Tens of thousands of hours of operational life at high rotational speeds are easily achievable with this type of unit. The major disadvantage of this brushless design is that the dual magnetic structures, synchro and transformer, do not allow the duplication of standard synchro parameters. In general, when compared with a standard unit, the brushless synchro or resolver will have higher power consumption, lower impedance angle, higher phase shift, and lower unit torque gradient. This can be a problem if the intent is to replace a synchro or resolver in an existing system. In new applications, proper design can allow for variations in unit performance. However, closer conformance to existing synchro performance can be achieved with additional unit length. Multi-phase rotors require additional length, since each rotor phase requires its own transformer.



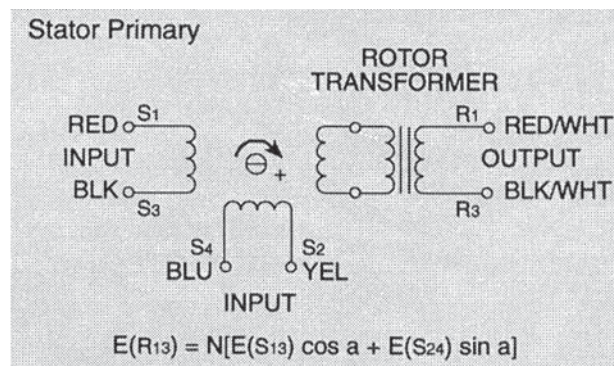
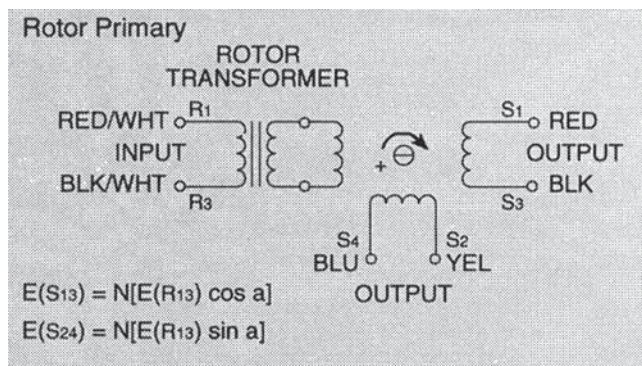


Figure 2.2.1 Schematic and Phasing Equation of Typical Transformer Type Brushless Resolvers

2.2.2 Hairspring Type

A hairspring brushless synchro is designed with spirally wound conductors used to transfer energy from/to the rotor. These hairspring conductors allow a limited rotation of as much as $\pm 165^\circ$ from the electrical zero position. The units are normally supplied with a mechanical stop to prevent damage to the hairsprings from excessive shaft rotation. The addition of the stop normally requires extra length. The advantage of hairspring over transformer-coupled brushless synchros is that any standard electrical characteristics can be duplicated in a hairspring design. If the application permits limited rotation, a hairspring unit can simply replace the

conventional unit already in the system. There is no effect on system performance except for the benefits from the elimination of sliding contacts. Properly designed hair springs will perform millions of operations without failure.

2.2.3 Flex Lead Type

A flex lead brushless synchro is designed with thin flexible lead wires to transfer energy from/to the rotor. These units have all the advantages of the hairspring type and are used in applications where short unit length and low friction are required. Rotation is usually limited to $\pm 90^\circ$.



3.0 Synchro and Resolver Parameters

3.1 Input Voltage and Frequency

Synchros and resolvers can be designed to operate with input voltages from 0.5 to 115 Vrms over a wide range of frequencies from 60 Hz to 100 kHz. Some of the standard input voltages are 11.8, 26, 90 and 115 Vrms. However, voltages between 5 and 26 Vrms and frequencies between 400 and 2600 Hz are preferred.

Depending on the size of the synchro or resolver, the input voltage and/or frequency may have to be limited so that an excessive input current will not saturate the iron core.

Synchros and resolvers can be operated at voltages and frequencies other than those specified, as long as the input current is not exceeded. If the frequency is doubled, the voltage can also be doubled. If the frequency is halved, the voltage must also be halved. However, some degradation in performance may be experienced at frequencies other than those specified.



3.2 Accuracy (Electrical Error)

The accuracy of a synchro or resolver is based on the ability of its output voltages to define the rotor angle. Of all the parameters, this is probably the most important. It is an exact measure of the function which the synchro or resolver is designed to perform. For any given rotor position, the output voltages are designed to give precise electrical information which corresponds uniquely to that rotor angle. Several methods are used to measure and define the error of a synchro or resolver. The most common ones are delineated below:

- (a) Synchro or resolver error is defined as the electrical angle, indicated by the output voltage,

minus the mechanical or rotor position angle. Electrical error is usually measured in arc minutes or arc seconds. The tangent of the electrical angle is calculated from the secondary voltages of all secondary windings (two for resolvers, three for synchros) when one primary winding is energized.

- (b) Function error compares the output of each winding separately. The error is defined as the difference between the in-phase component of the voltage of a secondary winding and the theoretical value of that voltage. This is expressed as a percentage of the maximum in-phase component of the secondary voltage and is equivalent to:

$$\left[\frac{E_{\alpha} - \sin \alpha}{E_{MAX}} \right] \times 100 = \% \text{Error}$$

where: E_{α} = The measured RMS value of the fundamental component of secondary voltage at any angle α .

E_{MAX} = The measured RMS value of the fundamental component of secondary voltage at a rotor angle $\alpha = 90^{\circ}$.

For standard synchros and resolvers, the functional error method is expensive. It is subject to errors and unsuitable for production testing.

- (c) Interaxis error is the angular deviation of all null positions for the rotor and stator combinations at rotor angles of 90, 180, and 270 degrees. This is expressed in arc minutes or arc seconds.
- (d) Linearity error describes the error of linear transformers. Linearity error is the nonconformity of the secondary voltage at any angular rotor displacement within the effective electrical travel limits. It is expressed as a percentage of the secondary voltage at the maximum excursion.
- (e) Velocity errors are caused by rotationally generated voltages. They are a result of conductors moving through a magnetic field (a synchro rotating at high speeds). Velocity errors are difficult to measure directly. Fortunately, many synchro/resolver applications operate in a virtual

static mode: rotational velocities are low. The increased use of these devices, especially brushless units, for high speed motor controls highlights the potential problem of inaccuracy in these systems.

The following formula is used to calculate the critical (synchronous) velocity:

$$S_c = \frac{120(F)}{P}$$

where: S_c = synchronous rotational velocity in RPM
 F = excitation frequency of the system in Hz
 P = the number of poles of the synchro/resolver

As a rule-of-thumb, speeds above one-quarter of synchronous speed cause serious velocity errors and should be avoided.

Example: A 32-speed (64 pole) resolver at 400 Hz has a synchronous velocity of:

$$S_c = 120 \times 400 / 64 = 750 \text{ RPM}$$

Therefore, rotational speed should be held below 180 RPM.



3.3 Transformation Ratio and Phase Shift

Transformation ratio (TR) is the ratio of output voltage to input voltage when the output is at maximum coupling. Practical TR'S usually range between 0.1 and 1.0. TR'S greater than 1.0 are sometimes possible, depending on the design of the unit. The most common TR's are .454 and 1.0.

Phase shift (expressed in electrical degrees) is the difference between the time-phase of the primary voltage and the time-phase of the secondary voltage when the output is at maximum coupling. Generally,

1-speed synchros and resolvers have leading phase shifts between 0° and 20° .

Phase shift can be approximated by the arctangent of the ratio of the primary winding DC resistance to its reactive component, as follows:

$$\text{Phase shift } \theta = \arctan \left[\frac{\text{primary } R_{DC}}{\text{primary } X_L} \right]$$

3.4 Voltage Sensitivity

Voltage sensitivity is the output voltage expressed as a function of the shaft angle in millivolts/degree. This parameter (also referred to as voltage gradient) is usually specified at a shaft angle of one degree. It can be calculated by multiplying the output voltage at maximum coupling by the sine of one degree.

3.5 Impedances

Impedances, expressed in ohms, are usually specified in rectangular form as $R + jX$ where R is the sum of the DC and AC resistive components and X is the reactive component. Impedances are sometimes expressed in polar form as $Z \angle \theta$ where Z is the total impedance and θ is the impedance angle. The impedances which are universally defined and apply to all synchro devices are:

ZPO: Primary impedance, secondary open circuit

ZPS: Primary impedance, secondary short circuit

ZSO: Secondary impedance, primary open circuit

ZSS: Secondary impedance, primary short circuit

For three-phase devices, the impedance is measured with two of the lead wires tied together. The impedance is measured between those two and the third wire.

The names "rotor" and "stator" are sometimes used in place of "primary" and "secondary." For example, for rotor primary units the primary impedances would be Z_{RO} and Z_{RS} . The secondary or stator impedances would be Z_{SO} and Z_{SS} .

For compensated resolvers, two additional impedances are required:

ZCO: Compensator impedance, secondary open circuit

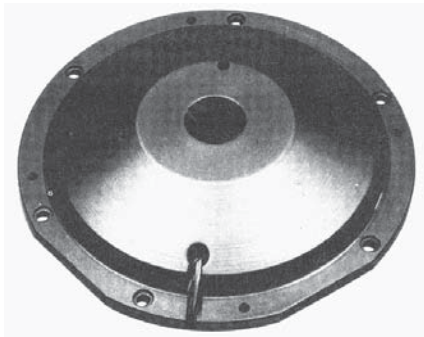
ZCS: Compensator impedance, secondary short circuit

3.6 Input Current and Input Power

Input current is the current, in amps, flowing through the primary winding at rated voltage and frequency. Input power, in watts, is calculated from input current and input impedance. In synchros and resolvers, input current is typically very low (less than 100 milliamps) and input power is usually less than 1 watt.

3.7 Null Voltage

Null voltage is the residual voltage remaining when the inphase component of the output voltage is zero. When the primary and secondary windings are exactly perpendicular (at electrical zero) there should be no induced voltage. The secondary voltage should be exactly zero. However, mechanical imperfections, winding errors, and distortions in the magnetic circuit (such as grinding smear), cause some voltage to be induced into the secondary at the minimum coupling position.



The null voltage is composed of three components: in-phase fundamental, quadrature fundamental, and harmonics. The in-phase fundamental component is an angular inaccuracy that can be cancelled out by renulling the rotor, thereby introducing an error (sometimes called null spacing error). Quadrature voltage is 90° out of time-phase with the in-phase component and cannot be nulled by rotor rotation. The harmonic voltages consist predominantly of the third harmonic which is three times the excitation frequency.

Null voltages are usually specified as total null voltage, which is the total of the quadrature fundamental and the harmonics.

Depending on size, input voltage, and input frequency, the total null voltage is approximately 1 to 3 millivolts per volt of input voltage. The

fundamental null voltage is usually slightly less than or equal to the total null voltage.

3.8 DC Resistance

DC resistance is the line-to-line resistance, measured in ohms, for all winding combinations at room ambient.

3.9 Dielectric Withstanding Voltage

A dielectric withstanding voltage test consists of applying a voltage higher than the rated voltage, for a specific time, between mutually insulated windings and between insulated windings and ground. (This is also called a high potential, Hi-Pot, or dielectric strength test.) This test is used to prove that a component can operate safely at its rated voltage and withstand momentary over-potentials due to switching surges. It determines whether the insulating material and the separation of the component parts is adequate.

When a part is defective, application of the test voltage will result in either disruptive discharge or deterioration.

Care should be taken when testing, since even an large voltage less than the breakdown voltage may damage the insulation and reduce the reliability of the unit. If subsequent application of the Hi-pot voltage is required, it is recommended that succeeding tests be made at reduced potential (usually at 80% of specified voltage).

3.10 Insulation Resistance

Insulation resistance is a measure of the resistance provided by insulating components to an applied direct voltage. Inadequate resistance permits leakage of current through, or on, the surface of these materials. Usually, the insulation resistance values in synchros and resolvers are very high (greater than 50 megohms). Low insulation resistances, by permitting flow of large leakage currents, can disturb the operation of circuits intended to be isolated. Excessive leakage currents can eventually lead to the deterioration of the insulation through heat or direct current electrolysis.

Insulation resistance measurements should not be considered the equivalent of dielectric withstanding voltage. Clean, dry insulation may have a high insulation resistance, yet have a mechanical fault that could cause failure in a dielectric withstanding voltage test. Conversely, a dirty, deteriorated insulation with a low insulation resistance may not fail a dielectric voltage.

3.11 Frequency Response

The frequency response of synchros and resolvers from input to output is similar to that of a transformer with a high leakage reactance. Low corner and peak frequencies will vary, depending on the impedance level of the unit. The low corner frequency is usually less than 100 Hz. The response is fairly flat from about 200 Hz to 10 kHz. A peak normally occurs between 10 kHz and 100 kHz.

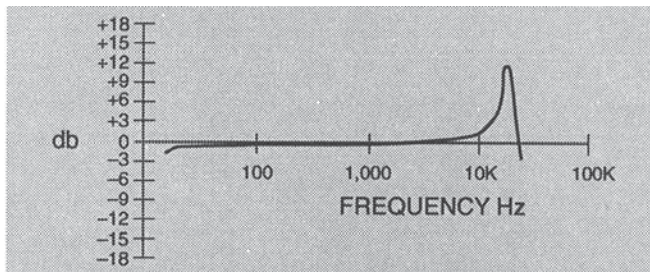


Figure 3.11 Typical One Speed Frequency Response

3.12 Harmonic Distortion

Harmonic distortion is an expression of the percentage of distortion in the output voltage. Typically, harmonic distortion in synchros and resolvers is less than two percent.

3.13 Loading

The electrical loading of synchros and resolvers should be ten or more times greater than the output short circuit impedance of the unit. More severe loads will decrease the output voltage, increase the input current, power, and null voltage, and degrade the accuracy.

3.14 Equivalent "T" Networks

To calculate the loading effect on synchro systems (commonly called synchro chains) each synchro can be treated as an equivalent "T" network. Chain parameters can then be solved (Figure 3.14). The formulas are based on line-to-line impedances when

the synchro or resolver is at maximum coupling. Z_{SO} for a three-phase winding is measured between two leads tied together and the third lead. Therefore the correction factor of 4/3 serves for all calculations.

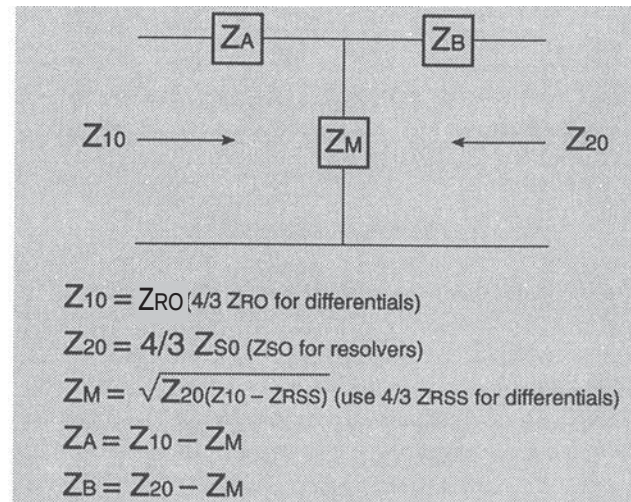


Figure 3.14 "T" Network Formula

3.15 Tolerances

Typical tolerances for the electrical parameters for standard synchros and resolvers at 25°C are as follows:

Input voltage	± 1%
Input frequency	± 2%
Input current	± 10%
Input power	± 20%
Output voltage or TR	± 3%
Phase shift	± 20% or 1 degree*
Null voltage	
26 volt synchros	30 mV max
115 volt synchros	100 mV max
Resolvers	1 mV/Volt of input

Impedances	
Open circuit.....R:	± 15% or ± 2 ohms*
Short Circuit.....R: ± 15% or ± 2 ohms*	
XL: ± 15% or ± 2 ohms*	
DC Resistances	± 10%

*Whichever is larger

Notes:

- 1) Null voltage is not measured on receivers.
- 2) Some brushless units, multispeeds, and non-standard units may have different tolerances. Please contact the Engineering Department.

4.0 Electrical Parameters vs. Temperature

All electrical parameters are specified at room ambient (25°C). In actual use the operating temperature may be different. The following are typical changes to be expected.

4.1 Accuracy (Electrical Error)

Theoretically, the error of a given unit should not change since errors are a result of design limitations and manufacturing inaccuracies. However, mounting stresses and differential expansion in the lamination stack, windings, and hardware due to temperature changes, may cause variations in a unit's error curve. The magnitude of the change will be different from unit to unit. Single speed units are more sensitive than multispeed units. A single speed may change as much as a few minutes, while a multispeed may only change a few seconds.

Even though there may be no change in the shape of the error curve, there is another factor which can add a bias. Referred to as EZ shift, this bias is due to a shift in the electrical zero resulting from minute mechanical changes with temperature. It cannot be predicted or calculated. The changes expected are similar to those mentioned above and are different from unit to unit.

4.2 Phase Shift

Resistive changes in the copper magnet wire result in changes in phase shift. The coefficient of resistance of copper is approximately 0.4% per degree C. Phase shift will change by the same percentage. Increased temperatures result in higher resistance and higher phase shift. Decreased temperatures produce the opposite effects.

As an example, for a unit with the following room temperature (25°C) input characteristics,

$$ZPO = 100 + j300$$

$$DCP = 60 \text{ ohms}$$

the phase shift Φ can be approximated as follows:

$$\Phi_1 = \arctan \frac{60}{300} = 11.3 \text{ degrees.}$$

Assuming an increase in temperature of 100°C (to 125°C), then:

$DCP = 60 \times (1 + .004 \times 100) = 84 \text{ ohms,}$
resulting in a new phase shift of:

$$\Phi_2 = \arctan \frac{84}{300} = 15.6 \text{ degrees.}$$

or an increase of approximately 4.3 degrees.

4.3 Transformation Ratio

Transformation ratio changes are related to changes in the phase shift. The change is proportional to the ratio of the cosine of the phase shift at the new temperature to the cosine of the phase shift at room ambient. Higher temperatures result in lower transformation ratios and lower temperatures result in higher transformation ratios. The new value may be calculated as follows:

$$TR_2 = TR_1 \frac{\cos \Phi_2}{\cos \Phi_1}$$

Where: TR_1 = TR at room ambient usually 25°C

TR_2 = TR at some other temperature

Φ_1 = Phase shift at room temperature

Φ_2 = Calculated phase shift at
temperature

Using the parameters from the above example and assuming a transformation ratio of .454, the new value will be:

$$TR_2 = .454 \times \frac{\cos 15.6}{\cos 11.3} = .446$$



4.4 Impedances, Input Current, and Input Power

Impedances, input current, and input power are also affected by a change in the resistance of the copper magnet wire.

The only change in impedance with temperature is in the resistive portion, the R component. Using the above example of an input impedance $Z_{PO} = 100 + j300$ (a total impedance $Z_T = 316.2 \angle 71.6^\circ$) with a DC resistance of 60 ohms, assuming an input voltage of 10 volts, and an increase in temperature of 100°C , the expected changes are calculated as follows:

Impedance:

The DC resistance changes as before:

$$60 \text{ ohms} \times 100 \text{ deg.} \times 0.4\% = 24 \text{ ohms}$$

Therefore the impedance at 125°C is:

$$Z_{PO} = 100 + 24 - j300 = 124 + j300 \text{ and} \\ Z_T = 324.6 \angle 67.5^\circ$$

Input Current:

The input current at room ambient is:

$$I_{IN_1} = \frac{E_{IN}}{Z_T} = \frac{10}{316.2} = 0.0316 \text{ amps}$$

And at elevated temperature is:

$$I_{IN_2} = \frac{E_{IN}}{Z_T} = \frac{10}{324.6} = 0.0308 \text{ amps}$$

Input Power:

The input power at room temperature is:

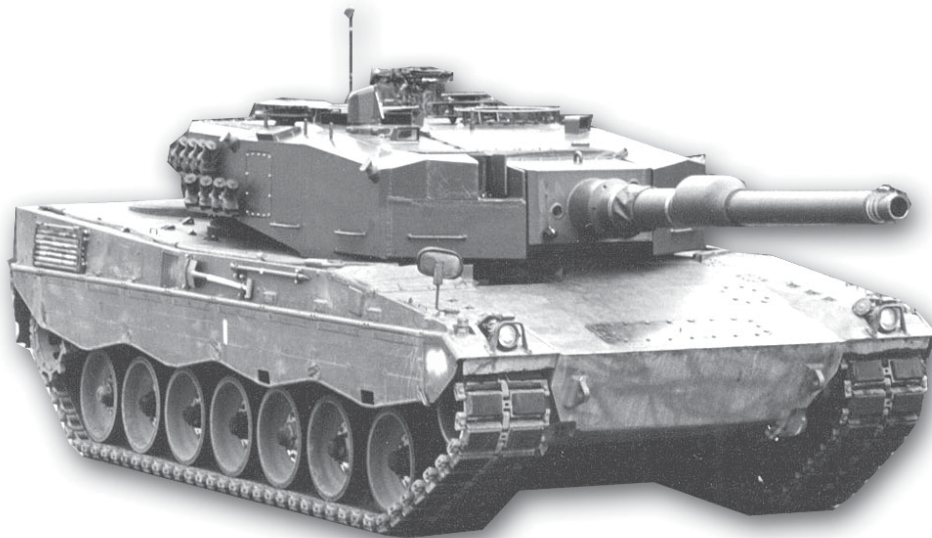
$$P_{IN_1} = (I_{IN_1})^2 R_1 = (.0316)^2 \times 100 = .100 \text{ watts.}$$

And at elevated temperature is:

$$P_{IN_2} = (I_{IN_2})^2 R_2 = (.0308)^2 \times 124 = .118 \text{ watts.}$$

4.5 Null Voltage

Null voltage is also sensitive to mounting stresses and differential expansion in the lamination stack, winding, and hardware due to temperature changes. Single speeds are more sensitive than multispeeds. The magnitude of the change will be different for various unit types and will be different from unit to unit for the same type. As a rule-of-thumb, the maximum change is less than 1% per degree C.



5.0 Mechanical Parameters and Mounting Considerations

5.1 Mechanical Parameters

Unhoused units, called pancakes, are inspected for all outline drawing dimensions. This includes outside diameter, inside diameter, and overall height. Housed units are checked for mounting dimensions and for conformance to shaft end play, shaft radial play, and starting friction requirements.

Shaft end play is the total axial motion of the shaft when an eight ounce reversing load is applied along the axis. Shaft radial play is the total side-to-side motion of the shaft measured as close to the bearing as possible, when a four ounce reversing load is applied radially to the shaft within 0.25 inch of the bearing. Starting friction is the torque necessary to overcome the internal friction of the bearings and brushes.

Because of the important relationship between accuracy, shaft end play, and shaft radial play, these parameters are controlled as rigidly as possible. If end play and radial play are too loose, higher errors and non-repeatability of the error pattern result. If they are too tight, performance over environmental service conditions may suffer. Friction, except in receivers, is relatively unimportant. A maximum friction of four gram-centimeters is an optimum level for both normal and extreme temperature ambients.



5.2 Mounting Considerations - Housed Units

Since most housed units have standardized sizes and are electrically coupled to the rotor by slip rings, hairsprings or transformers, the mounting considerations are minimal. The two major areas of concern are the housing mounting and the shaft coupling.

Normally the housing is mounted into a pilot diameter and then secured in one of two ways. The first is by means of synchro clamps mounted and secured adjacent to the pilot diameter in the circumferential groove in the housing. The second method is to secure the housing with screws entering the mounting face. If clamps are used, especially for resolvers, two or four point contact is suggested.

Coupling to the shaft is accomplished by means of a solid coupling to another shaft, a bellows type coupling, or by a gear arrangement. Care must be taken to avoid applying excessive radial loads to the shaft.

5.3 Mounting Considerations - Unhoused Units

Unhoused units are usually supplied as separable rotors and stators to be directly mounted in the housings and on the shafts of the user's system.

If an unhoused unit is to be used for other than very limited angular rotations, some means must be provided to couple electrically to the rotor windings. This is usually accomplished with slip rings mounted to the user's shaft adjacent to the rotor. A true brushless unit can be used, if space and electrical parameters permit, eliminating the need for slip rings.

The user, providing the mounting surfaces and bearings when he designs the mechanics of the mount, should consider these guidelines:

1. Eccentricities between the inner and outer member mounting surfaces should not exceed 0.0005 inch.

2. Mounting shoulders should be perpendicular to bores and shafts within 0.0005 inch.
3. The fit between the bore and the maximum stator OD and between the shaft and the minimum rotor ID should be from 0.0002 to 0.0007 inches loose. This will assure that there is no line-to-line or interference fit.
4. Axial misalignment or variation in mounting dimensions between the rotor and the stator mounting surfaces should not exceed 2% of stack height. In other words, for a stack height of 0.250 the axial misalignment should not exceed 0.005 inch.
5. The designer should select housing and shaft materials with thermal coefficients of expansion similar to that of the unit's ring material or, if it has no rings, it's lamination material, usually a high nickel steel.

The above guidelines are for a typical unit. Depending on unit size, air gap clearance, accuracy, and other electrical requirements, these guidelines may require looser or tighter tolerances.

5.4 Effects of Improper Mounting

If, due to system tolerance buildup or defective system hardware, the preceding guidelines are exceeded, some changes in electrical characteristics can be anticipated.

The magnitude of these changes will depend upon unit size, air gap clearance, and whether it is a single speed or multispeed. The performance of the unit will be affected as follows:

1. For axial offset:

- Accuracy (electrical error) will increase only slightly
- Null voltage will change
- Transformation ratio will decrease
- Phase shift will increase
- Input current and power will increase

2. For radial offset:

- Accuracy (electrical error) will increase proportionally
- Null voltage will change
- Transformation ratio will show little change
- Phase shift will show little change
- Input current and power will show little change

3. For rotor and stator tilt:

If rotor and stator tilt is slight, (about 0.001 or 0.002 inches with respect to each other), very little change will occur in any parameter. Tilts greater than this must be avoided in units with small air gap clearances to prevent rotor and stator from making contact.



6.0 Multispeed Synchros and Resolvers

Multispeeds are electronically and mechanically similar to standard synchros or resolvers. Their name is derived from the following relationships: For every mechanical revolution of the rotor, the unit electrically produces “N” cosine waves on the cosine output winding and “N” sine waves on the sine output winding. “N” is the ratio or the “speed,” which is one half the number of poles. A 36 speed, for example, has 72 poles (36 pole pairs) and appears to be mechanically geared through a 36:1 ratio. Multispeed synchros have three output phases spaced 120° apart electrically, and multispeed resolvers have two output phases spaced electrically 90° apart.

The beginning of each sine cycle is designated as an electrical zero (EZ) point. The deviation of all these points from the theoretical true position is called the cross-over error. The exploration of the deviation from the true value for each sine and cosine output over each individual cycle is called a tangent error. This evaluation, using a tangent bridge and a null meter, is identical to that performed on a normal speed synchro or resolver.

Multispeed units have one cycle (360 electrical degrees) in 360/N mechanical degrees. This may present an ambiguity to the user, unless the total excursion angle is less than one cycle. To be able to distinguish between the individual electrical cycles, a conventional single speed is inserted in the same slots with the multispeed, creating a multiple speed unit. (see Figure 6.0). For example, a 1-speed and a 36-speed will give a cycle (2 pole) output at one set of output windings and a 36 cycle (72 pole) output at the other. The 1-speed portion is generally called the coarse output and the 36-speed portion is called the fine output. The Master EZ is defined as that multispeed EZ closest to the start of the 1-speed sine curve.

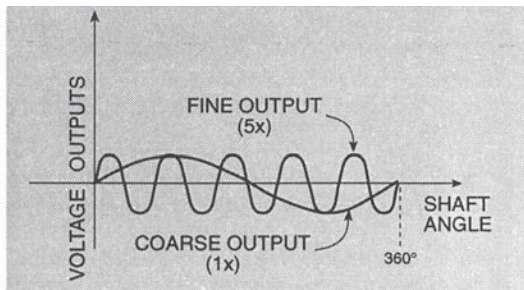


Figure 6.0 Superimposed Output Waveforms for Coarse (1-speed) and Fine (5-speed) Resolver



6.1 Multispeed Characteristics

All the information on synchro and resolver characteristics presented earlier in this manual applies equally to multispeeds. There are, however, additional factors to be considered when selecting the proper multispeed for a specific application. This chapter will highlight the options and variations the user should consider.

6.2 Speed vs. Size

Typical multispeed synchros and resolvers range in size from 1.1 inches (1-8x) to more than 3 feet (1-150x) outside diameter.

The table below presents a guideline of practical dimensions for common speed ranges:

Speed	O.D.	I.D.	O. A. Width
64 or 72	4" - 6"	2" - 4"	1"
32 or 36	3" - 5"	1" - 3"	.75"
8 or 16	2" - 4"	.5" - 2"	.50"

For a given speed, a large mechanical cross section increases the rigidity of the unit. This provides stress resistance to support the increased number of teeth required for the greater number of poles.

6.3 Accuracy

The accuracy curve of a multispeed consists of three individual components:

Mechanical, electrical, and slot ripple errors. Mechanical error, caused by out-of-roundness, tilt,



eccentricity, bearing run-out, and mounting stresses, can be observed in the cross-over error curve.

Electrical errors, such as transformation ratio unbalance or perpendicularity (sine and cosine zero crossings not exactly 90 electrical degrees apart) will surface in the tangent error curve. Electrical errors can usually be designed or compensated out of a unit. The main remaining errors will consist of mechanical and slot ripple errors. Slot ripple is due to the interaction between rotor and stator teeth. It can be minimized by proper slot combination and/or skewing of the slots. Typical errors for existing multispeed units are 20 arc seconds for a 36- or a 64-speed, 30 arc seconds for a 16-speed, and 60 arc seconds for an 8-speed.

6.4 Coupling Factor

An increased winding turns ratio (secondary to primary) is required because of the lower magnetic coupling in multi-speed devices due to the larger number of slots necessary.

Example: For a single speed unit with a 1:1 TR (transformation ratio), the turns ratio would be approximately 1.05:1. For a 16-speed unit it would be approximately 2:1; for a 36-speed unit 2 1/2 or 3:1; for a 64-speed unit as high as 3 1/2 or 4:1 for the same TR.

To provide a reasonably high impedance, the transformation ratio for multispeeds should be limited to the following maximum values:

8-speed	.75
16-speed	.50
36-speed	.30
64-speed	.20

6.5 Voltage Sensitivity

The voltage sensitivity of multispeeds is the output voltage expressed as a function of the shaft angle times the speed of the unit.

This parameter (also referred to as voltage gradient) is usually specified at a shaft angle of one degree mechanical. For example, a 4-speed with a maximum output voltage of 11.8 volts has a voltage sensitivity of:

$$11.8 \times \sin (1 \times 4) = 0.023 \text{ volts/degree.}$$

6.6 Impedance Levels

Secondary open circuit impedances are usually higher on multispeeds. The undesirable characteristics of the loading effect from additional units in a chain is offset since multispeeds are relatively insensitive to loading. If a lower short circuit impedance is required, the input impedance can be decreased, increasing the power level, or the transformation ratio can be reduced. Impedance imbalances, both resistive and capacitive, are lower than on single speed units.

In some cases, a low output impedance may be necessary to prevent capacitive coupling between the output windings. Capacitive coupling is an apparent current flow between the sine and cosine windings. It produces an error that can increase electrical perpendicularity to such an extent that manual compensation may be impractical.

6.7 Phase Shift

The increased number of slots required by the larger number of poles, results in smaller slot areas than those used in conventional single speed units. This necessitates a finer wire for the windings. In addition to the smaller pole span ratio, this will normally result in a much higher phase shift than that of a comparable single speed device. For example, for a given stack size, a unit wound as a regular one speed might have a phase shift of approximately 4°. The phase shift could be 20° for a 16-speed, 35° to 40° for a 36-speed, and as high as 60° for a 64-speed.

6.8 Transformation Ratio vs. Air Gap

One of the critical characteristics of the multispeed unit is its sensitivity to overall air gap size. For example, a single speed unit with a radial air gap of .006" and a transformation ratio with a tolerance of 2%, would probably stay within the tolerance even if the air gap were ground .0005" over or under nominal. On multispeed units, however, the 2% tolerance would be exceeded for the same air gap variation. The higher the speed, the more pronounced the effect. If a 64-speed unit with a radial air gap of .006" is 0.0005" oversize, its transformation ratio can change by 10%. This puts an increased burden on the manufacturer of the device to hold tolerances much more closely than on single speeds. Typical transformation ratio tolerances for multispeed units should be specified as follows:

8-speed	4%
16-speed	5%
36-speed	6-7%
64-speed	Up to 10%

6.9 EZ Coincidence

EZ coincidence is the mechanical angle between the fine and course speed electrical zeros of a multispeed synchro or resolver. This angle can be included in the coarse speed accuracy specification, and acts as a bias to the error curve of the one speed.



6.10 Cross Coupling

Cross coupling is the effect that a single speed input winding has on a multispeed output winding and vice versa. Null voltages and errors usually increase, compared with values for the unit when energized and tested individually. Careful design can usually reduce these effects to less than a few millivolts and insignificant changes in the error curves.

6.11 Frequency Response

The frequency response of a multispeed is similar to that of a one speed, except that it is not quite as linear in the mid frequency range. At higher frequencies, between 10 kHz and 100 kHz, two peaks occur.

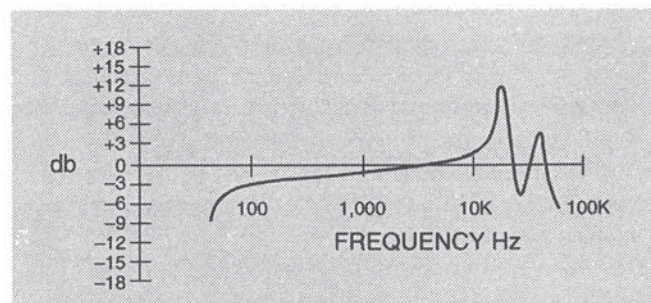


Figure 6.11
Typical Frequency Response of Multispeeds

6.12 Instrumentation and Test Procedures

Instrumentation for testing multispeed devices is very much the same as that used for high quality single speed units. The synchro or resolver bridge used to test the tangent error is normally accurate to within two to four seconds. This is sufficient for even the best multispeed, since the error of the bridge is divided by the speed of the resolver. A 2 arc second bridge error becomes .125 arc second for a 16-speed unit and even less for a 64-speed unit.

With phase angle voltmeters of sufficient accuracy, the weak links in the instrumentation chain become the mechanical mounting and the readout of angular errors. Several instruments are available that will suffice for testing very high accuracy units.

6.13 Variable Reluctance Multispeed

Variable reluctance multispeeds have both the input and the output windings on the stator (the outer element) and no windings at all on the rotor. They are therefore true brushless devices. The rotor has a number of teeth equivalent to "N", the speed of the unit. This type of design is therefore impractical for single speeds, since the rotor would only have one tooth. Units of this type are actually the original version of the multispeed resolver or synchro. They took the place of geared single speeds.

The position of each tooth during the rotation of the rotor determines which of the output windings will be coupled to the input winding to produce an output signal. All coupling conditions repeat themselves every time a tooth moves to the position where an adjacent tooth was previously. When this happens, a complete cycle (360° electrical) of the sine and cosine has taken place.

This highlights the disadvantage of this design. Each crossover (where the sine crosses from minus to plus) is well defined by the mechanical precision of the rotor teeth, but the point where the sine crosses from plus to minus (180° electrical) is floating. It is defined by the lack of a tooth. This results in much larger tangent errors than those of rotor wound multispeeds.

The following list serves as an example of the expected range of errors for similar sized units:

	Wound Multispeeds	Variable Reluctance Multispeeds	
Speed	Overall Error (arc minutes)	Cross-over Error (arc minutes)	Tangent Error (arc minutes)
2	3-7	2-3	70-90
4	.5-4	1-2	60-80
6	.5-3	1-2	40-60
8	.3-1	.5-1	20-40
16	.2-.5	.3-.7	15-20
32	.2-.3	.2-.5	10-15
64	.1-.2	.2-.3	5-10

Variable reluctance multispeeds are now successfully used as commutation transducers for brushless motors. In many cases, they are more reliable and environmentally stable than other types of devices.

6.14 Sectional Components

Sectional resolvers, synchros, and linear transformers are hybrid variations of standard units. These components distinguish themselves from all the others previously discussed by their lack of symmetry. While typical resolver functions rely on symmetrical, round and concentric air gaps, the rotors and stators of these devices are built as arc segments.

Useful rotation of the rotor must be strictly limited, unless a lack of signal for a large part of the travel is allowable. Mounting of these devices is more critical than that of standard synchros. Any air gap variations due to eccentricities or rotor movement toward or away from the stator element will result in errors.

Applications range from a gun turret direction indicator using a quasi-single speed device to a partial 16-speed mirror elevation control unit. Apparent diameters vary from a few inches to more than 10 feet. Accuracies range from 5 arc minutes to 20 arc seconds.



7.0 Resolver to Digital Conversion

7.1 Angular Measurement Devices

Two types of components are commonly used to make angular measurements: encoders and resolvers. A short description of these can help in optimizing component selection for specific applications.

7.1.1 Encoders

An encoder is an electro-optical device which uses a glass disk inscribed with fine lines. The number of lines determines resolution and accuracy. There are two basic types of encoders: incremental and absolute.

An incremental encoder produces output pulses as its shaft is rotated. The direction of rotation is determined by the phase relationship of two output lines. A third line is used as a reference when the encoder passes thru zero.

The disadvantage of an incremental encoder is that on power up or after a power interruption the true angular position is lost and the system has to be reinitialized.

Absolute encoders give a parallel digital signal indicating shaft position. However, this requires extra lines to send a signal to the digital processor. A unit with an accuracy of 20 arc seconds will require 16 wires.

The advantages of encoders are that they have digital outputs, are easily computer interfaced, and are generally well understood. The primary drawbacks of encoders are: sensitivity to hostile environments, reliability problems in certain applications, and size of a given resolution and accuracy.

7.1.2 Resolvers

A resolver is an electro-mechanical transformer whose analog output voltages are a function of shaft angle. It is, therefore, an absolute position transducer, providing true angular information at any time power is applied.

The advantages of a resolver are that it can be easily

mounted where an angle needs to be measured and the electronics can be located in a less hostile electronic equipment area. Signal transmission requires only four signal lines for a single speed and eight signal lines for a high precision multispeed resolver. A resolver also provides signal isolation and common-mode rejection of electrical interference, and can withstand severe environments of dust, oil, temperature, shock, and vibration.

Disadvantages of resolvers are that they require an AC signal source and that their analog output must be converted in interfacing with digital systems.

7.2 Angle Transmission Using Resolvers

There are several methods of using a resolver to obtain precise shaft angle position.

7.2.1 Direct Angle Technique

In the direct angle method, the rotor winding is excited by an alternating signal and the output is taken from the two stator windings. Both outputs have nearly the same time phase angle as the original signal. However, their amplitudes are modulated by sine and cosine as the shaft rotates.

These outputs are fed to either a receiving type resolver (resolver chain) or to an analog-to-digital converter. Recent advances in conversion techniques and manufacturing have simplified the electronic interface.

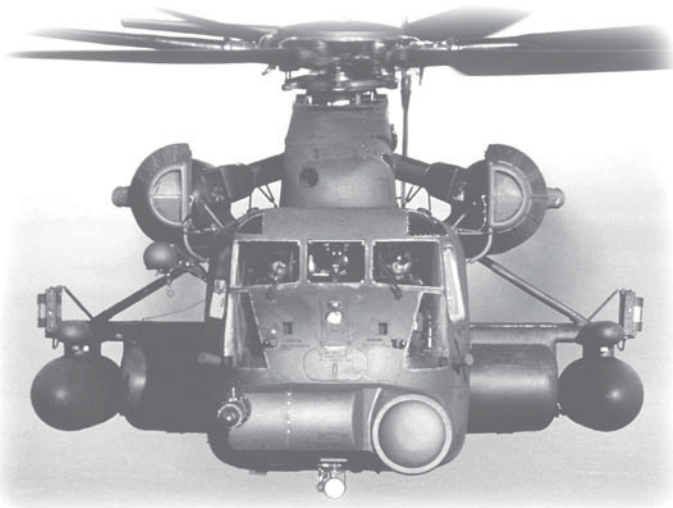
Sources of error for this method are the resolver accuracies and, if used, the converter accuracy and resolution.

7.2.2 Phase Analog Technique

In this method, the two stator windings are excited by signals that are in phase quadrature to each other. This induces a voltage in the rotor winding with an amplitude and frequency that are fixed and a time-phase that varies with shaft angle. This method is referred to as the "phase analog technique." It has been the most widely used technique since it can easily be converted to produce a digital signal by measuring the change in phase shift with respect to the reference signal.

The accuracy of this type of angle transmission is determined by the accuracy to which the zero crossing intervals can be measured.

Sources of error for this method are noise generated by the environment of the resolver. This causes the zero crossing point to be indeterminate and produces variations in the excitation. Any variation of the amplitudes or time-phases of the two excitation signals directly influences the time phase of the output signal.



7.2.3 Sampling Techniques

When using this method a sample is taken of the sine and cosine output signals of a rotor excited resolver at the peak of the reference input amplitude. These are converted to digital signals by an analog to digital converter. The resulting digital words are used as a memory address to “look-up” the shaft angles in a processor.

The difficulty with this approach is its inability to deal with noise. If a noise disturbance occurs on the signal lines at the time of sampling, a wrong shaft angle position results. If the noise causes only a single wrong reading, the frequency pass band of the drive systems acts as a filter with little resulting error.

7.2.4 Tracking Resolver to Digital Converter

The tracking conversion technique overcomes all the difficulties described above. Modern converters are cost competitive with other methods and provide superior accuracy and noise-immunity. A tracking

converter operates ratiometrically. It uses only the ratio of the sine and cosine stator outputs of a rotor excited resolver. Since the resolver acts as a transformer, any excitation waveform distortion or amplitude variation appears in the correct ratio on both sine and cosine and has little effect on accuracy. A tracking converter contains a phase demodulator. Therefore, frequency variation and incoherent noise do not affect accuracy. Tracking converters can operate with any reference excitation, sine or square wave, with only minor accuracy variations. Common mode rejection is achieved by the isolation of the resolver.

7.2.5 Dual Converters

Dual converters are used to encode the resolver or synchro of multispeed units. One channel, the coarse portion of the converter, is connected to the single or coarse speed section of the resolver. The other channel, the fine portion, is connected to the fine speed section.

The coarse channel supplies an approximate non-ambiguous rotor position to the demodulator. When the output error of the coarse channel drops below a preset threshold, the crossover detector switches the fine channel error signal into the demodulator. The error angle is multiplied by the speed ratio of the resolver. This increases the voltage sensitivity and enables the servo system to seek a more accurate null. The converter will continue to use the fine error signal for continuous tracking.

The basic accuracy and resolution of the converter is therefore divided by the speed of the resolver.

Example: A 16 bit converter with an accuracy of 2 arc minutes has a single speed resolution of 20 arc seconds. This can be coupled with a 32-speed ($32 = 2^5$ bits) resolver. The resulting converter accuracy is $2 \times 60/32 = 3.75$ arc seconds. The system resolution is 16 bits +5 bits or 0.6 arc seconds.

7.3 Practical R/D Converter Application

Figure (7.3) shows a complete R/D converter schematic. The 16 data lines and the seven control lines are buffered by two 74LS245 and one 74LS244 IC's respectively. These parts are used to isolate the R/D converter from static electricity, and to increase the drive capability for an LED display.



In this schematic, the carrier reference is a symmetrical square wave drive. It consists of U14, the oscillator; U15A, a divide by flip-flop used to product a symmetrical waveform; and U17 and U18, which are LM555 timer I.C.'s used as power drivers. If noise is a problem an OSC1758 sine wave oscillator can be substituted for the U14, U15, U17 and U18.

The heart of the converter is U11, which is a typical 16 bit parallel R/D converter I.C. This device (a 2S80 is shown) can be programmed for a resolution of 10,12, 14, or 16 bits. and an accuracy of 2 minutes at 16 bits. At the 10 bit resolution, the maximum tracking rate is over 62,000 RPM.

This chip also has a linear velocity output. Therefore, no separate tachometer is needed to measure angularity velocity with a single that is linear to 1%. The tracking R/D converter generates a digital word which tracks the input position with no time lag. The digital output is always within one LSB (least significant bit) of the input signal, up to the maximum tracking rate of the converter.

The circuit shown provides a 16 line bar code display and a four digit hexadecimal display for testing and evaluating a resolver.

7.4 Resolver Commutation of Brushless Motors

One of the most cost effective methods for commutation in a brushless motor is the use of the Hall effect switch and a magnetic code wheel to sense the position of the motor as it rotates.

The Hall switch is an integrated circuit that is limited to temperature extremes of -55 to 125°C. Hall switches are available that operate at 150° C but are limited to an operating life of 100 hours at this temperature. Among other limitations, they cannot provide accurate position and velocity information. A resolver can operate at much higher temperatures than integrated circuits, even above 180° C. The actual operating temperature is a function of the unit's material and type of construction.

7.4.1 Resolver to Digital Converter

A converter as shown in Figure 8.3 can also be used for motor commutation. Digital angle information can be converted to commutation signals by adding a PROM Look-Up Table to the digital data.

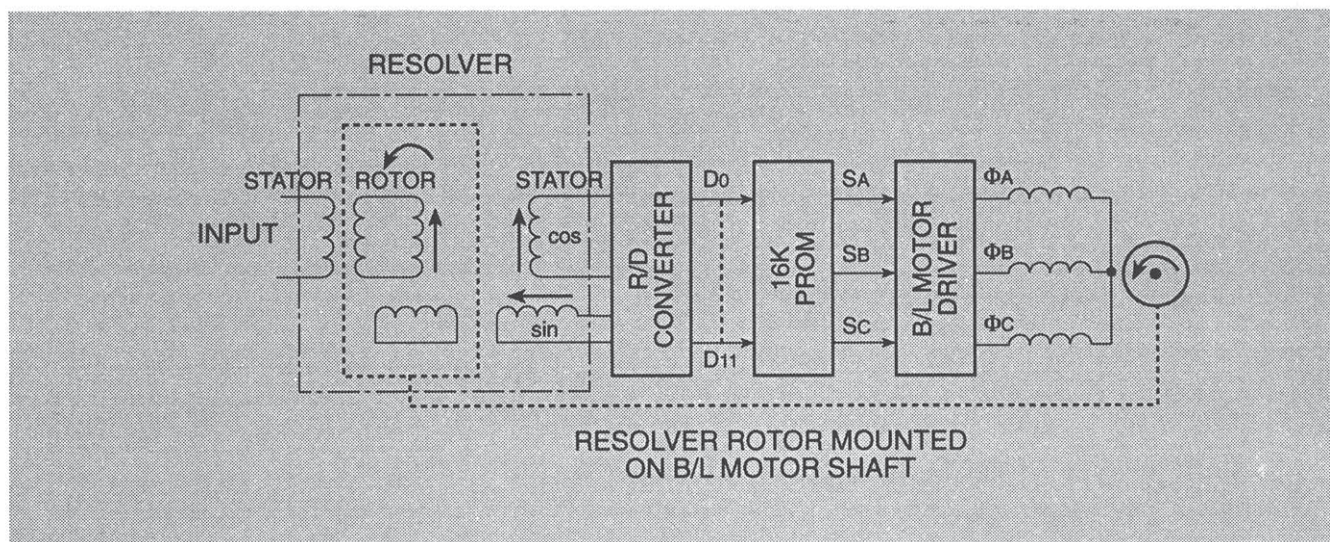


Figure 7.4.1 Typical Brushless Motor Drive Using a Resolver to Digital Converter

In a typical 12 bit converter (see Figure 7.4.1) there are 4096 (4K) states that have to be decoded. A three-phase brushless motor drive has six drive signals for the six power driver transistors. It requires six 4K x 1 PROMs or one 32K PROM (4K x 8). An existing brushless motor driver can interface with Hall switches, the R/D converter and the driver with three 4K x 1 PROMs or one 16K PROM (4K x 4).

7.4.2 Synchronous Demodulation

An R/D converter as described above is not necessarily required when using a resolver to commutate a brushless motor. If the only requirement is to rotate the motor and accurate position data are not required, a synchronous demodulator can be used to process this information.

A three-phase motor will require a three-phase synchro, usually with the same number of poles as the number of magnet pole reversals in the motor. An 8-pole motor has 4 pole reversals per revolution. A 4-speed (8-pole) synchro would be ideal as a commutator. Most commutation can be done with either 2- or 4-speed brushless synchros.

A synchro that is used only for commutation is more economical than a unit designed to provide high accuracy angular information, since the analog output is of little importance. The significant parameter is the zero crossing error. Careful mechanical design can make this very accurate.

Figure 7.4.2 (a) shows a block diagram for a typical commutation circuit. U1, U2, and U3 are phase demodulators. One is required for each output of the synchro. This integrated circuit separates the carrier frequency from the modulation frequency (motor rotation). It produces a sine wave which is then level shifted and amplified by U4A, U4B, and U4C to produce three digital outputs. At this point the outputs A, B, and C are the same as those produced by the Hall devices and can be handled by standard brushless motor drivers.

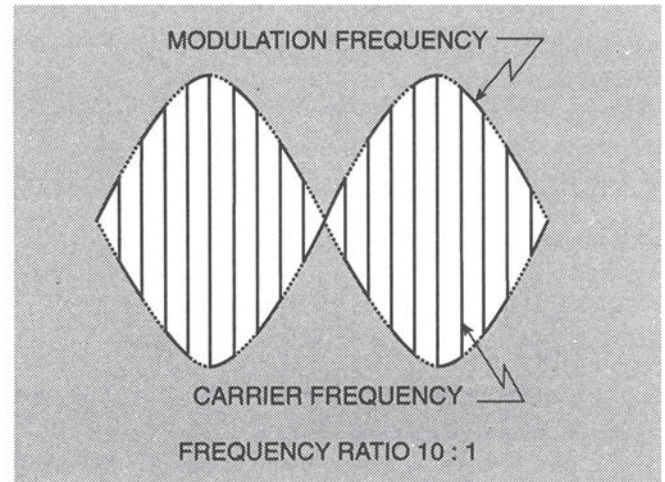


Figure 7.4.2(b) Modulated Synchro Output

Figure 8.4.2(b) shows one of the three outputs from the synchro as the motor is rotating. All three outputs are the same except that they are shifted in phase by 120 degrees.

In this design the carrier frequency should be at least ten times greater than the highest frequency of the motor. For a motor that operates at a maximum of 5,000 RPM the carrier frequency should be higher than 800 Hz. The shape of the carrier frequency has little effect on the performance of the circuit. A square wave is the least expensive to generate, while a sine wave is optimum for system noise reduction.

8.1 Reliability

Since they are inductive devices, synchros and resolvers have a very long life expectancy. The nature of a transformer permits the isolation of the input and the output circuits. The shortest life expectancy would be expected for units with brushes and slip rings, the longest for true brushless units using rotary transformers.

An average value for Mean Time Between Failures (MTBF) cannot be stated because of the many factors that influence the calculation.

The best guide available for MTBF calculations is in the US Department of Defense Handbook MIL-HDBK-217. This handbook lists the many factors that affect synchro and resolver failure rates and defines a method of estimating them. It takes the following factors into account:

- Ambient temperature
- Temperature rise of the unit
- Size of unit (Size 8, 10, 11, 15, etc.)
- Number of brushes
- Type of application (e.g., ground, vehicle mounted ground, shipboard, airborne, missile)

As an example, for a Size 8 synchro with two brushes operating in a Ground Benign service environment, with a frame temperature of 70°C, and an internal heat rise of 5°C, the failure rate calculates to 0.062 failures/million hours. This translates to an MTBF 16.18 million hours or 1,847 years.

8.2 Environmental Requirements and Military Specifications

The following military standards cover many environmental service conditions to which our standard synchros have successfully demonstrated conformance. This list is by no means all-inclusive. nor does it hint at the ultimate limits of our units' capabilities. Rather it is meant as a guide for

establishing specifications for synchros which must withstand environmental operating extremes.

Vibration:	MIL-STD-202G, Method 204D, Cond. B SAE AS20708, Paragraph 3.7.1
Shock:	MIL-STD-202G, Method 213B, Cond. A SAE AS20708, Paragraph 3.7.2.1 (Low Impact)
Altitude:	MIL-STD-202G, Method 105C, Cond. A, B, C, or F
Humidity:	MIL-STD-202G, Method 103B, Cond. A or B; Method 106E SAE AS20708, Paragraph 3.7.6 MIL-STD-810E, Method 507.1, Procedure I
Ambient Temperature:	SAE AS20708, Paragraph 3.7.5 MIL-STD-810E, Methods 501.1 and 502.1
Thermal Shock:	MIL-STD-202G, Method 107D, Cond. A or B
Explosion:	MIL-STD-202G, Method 109B
Salt Spray:	SAE AS20708, Paragraph 3.7.8
Fungus Resistance:	MIL-STD-810E, Method 508.1
Endurance:	SAE AS20708, Paragraph 3.7.4 1000 hrs. min. at 100 rpm

9.0 Storage, Handling and Installation

9.1 Storage and Handling

Synchros and resolvers are supplied in either of two ways: as completed housed units, or as unhoused rotors and stators. Most pancake designs are unhoused and may or may not have mounting rings. Unhoused units are manufactured in matched sets and should not be interchanged.

9.1.1 The units should remain in their original packages until ready for use and should be stored at room ambient in a clean dry area.

9.1.2 Care in handling must be exercised at all times.

9.1.3 Use care when mounting and removing parts to avoid damage to mounting surfaces, mounting diameters, shafts, and air gap surfaces.

9.1.4 Avoid pinching or cutting lead wires. Be careful not to damage terminals or connectors.

9.1.5 Do not drop parts or subject them to radial forces (squeezing a diameter). This could cause magnetic changes, affecting the performance of the unit.

9.1.6 Never machine or drill housings, rings, shafts, or lamination stacks. Internal damage, bearing contamination, or magnetic changes could occur.

9.2 Installation

9.2.1 Housed units require no special procedures except for the normal care required as stated above.

9.2.2 Unhoused units require more care than housed units. Stators and rotors should be placed in position with care so that parts do not become cocked. In no case should these parts be pressed into holes or onto shafts. Press fits should never be used, since this would cause physical or magnetic damage.



10.0 Definitions and Terminology

Accuracy (Electrical Error): Electrical angle, as indicated by the output voltage, minus the mechanical or rotor position angle.

A/D Converter: Analog to digital converter, used to convert common audio or video signals to digital for computer interfacing.

Barcode Display: A set of simple ON/OFF lamps that indicate the status of a digital output signal from an A/D or R/D converter.

Brushless: Transferring energy from or to a rotor by means of a circular rotary transformer, spirally wound conductors (hairsprings), flex lead or variable reluctance.

Common Mode Rejection: Rejection by an input device of large unwanted in-phase input noise without affecting a small out-of-phase signal.

Compensated Resolver: A synchro with feedback windings in parallel with primary windings.

Control Synchro: A synchro used to provide and deal with control signals in servo systems where precise angular transmission to a mechanical load is required.

Control Transformer: A synchro with a three-phase primary winding, usually on the stator, and a one-phase secondary winding. This is a high impedance version of a torque receiver. It is excited by other synchros.

Control Transmitter:

Crossover Errors: The deviations of all the crossover points (sine output voltage passing from negative to positive) from a master electrical zero of a multispeed synchro or resolver.

Differential: A synchro with a three-phase primary winding and a three-phase secondary winding. This is an analog form of mechanical differential.

Differential Resolver: A hybrid synchro with a three phase rotor winding and a two-phase stator winding. This is the reverse of a transolver. It can be used in either direction as a transmitter or control transformer.

Electrical Error: See Accuracy.

Electrical Zero (EZ): The rotor angle at which the sine output voltage is at an in-phase null.

End Play: The total axial motion of the shaft when a specified reversing load is applied along the shaft axis.

Excitation: The RMS voltage and frequency which excites the primary winding.

EZ Coincidence: The mechanical angle between the fine and course speed electrical zeros of a multispeed unit.

Friction: The torque required to turn a shaft from a stationary position.

Function Error: The difference between the in-phase component of one secondary winding voltage and the theoretical value of the secondary voltage. This is expressed as a percentage of the maximum in-phase component of the secondary voltage.

Hairspring: A spirally wound conductor, used for limited rotation, to transfer energy to or from the rotor. It can be used up to ± 165 degrees.

Hexidecimal: A convenient means to display the 16 possible states of a 4 bit binary word on a seven segment display:

0123456789AbCdEF

Input Current: The current, in amps, flowing through a primary winding when excited at rated voltage and frequency.

Input Power: The power, in watts, consumed by a primary winding when excited at rated voltage and frequency.

Interaxis Error: The angular deviation of the null positions for all rotor and stator combinations at rotor positions of 90, 180, and 270 degrees.

Impedances:

ZPO: Primary impedance, secondary open circuit

ZPS: Primary impedance, secondary short circuit

ZSO: Secondary impedance, primary open circuit

ZSS: Secondary impedance, primary short circuit

ZCO: Compensator impedance, secondary open circuit

Zcs: Compensator impedance, secondary short circuit

Linear Transformer: A synchro with one-phase primary and one-phase secondary. The generated output voltage at any given rotor angle within the rated excursion is directly proportional to that angle.

Master EZ: The multispeed electrical zero closest to the single speed electrical zero.

Mechanical Zero: The angle at which the rotor and stator are mechanically aligned by markings, pins, slots, etc., usually close to the electrical zero.

Multiple Speed: A synchro with a coarse and a fine speed winding in the same lamination stack, usually referred to as a multispeed.

Multispeed: A synchro that produces for one mechanical revolution of the rotor “N” sine and “N” cosine waves at the output windings. “N” is the speed. There are two poles per speed. The name can apply to resolvers or synchros and is commonly used for multiple speed.

Null Voltage: The residual voltage remaining when the in-phase component is zero. The total null voltage is the sum of the quadrature fundamental null voltage plus the harmonics.

Output Voltage: The no load voltage at the secondary windings at maximum coupling with rated voltage and frequency applied to the primary winding.

Pancake: A name given to synchros and resolvers which are flat in appearance. The term is derived from the physical dimensions of these units which typically have a diameter that exceeds the axial length.

Phase Demodulation: A technique for detecting signals with a large degree of rejection of frequencies outside the single band.

Phase Shift: The difference between the time phases of the primary and secondary voltages when the output is at maximum coupling.

Primary Winding: The winding which receives power from another component or from a power supply.

Radial Play: The total radial movement of the shaft on it's own bearings, measured on the shaft at a specified distance from the housing when a specified reversing load is applied radially to the shaft.

R/D Converter: Resolver to digital converter. This type of device is used to convert the analog output of a resolver to a digital signal.

Receiver: A synchro with a line excited rotor within a three-phase stator connected to the corresponding stator leads of a driving torque transmitter.

Resolver: A synchro with a one-or two-phase primary and a two-phase secondary that creates or receives sine-cosine signals.

Secondary Winding: An output winding which is inductively coupled to a primary winding.

Sensitivity: Is the output voltage at one mechanical degree. Is defined as the maximum output voltage times the sine of 1 degree, and is expressed in mV/ DEG.

Synchros: Rotating, transducing devices of various types, used to convert shaft angle position to electrical signals or the reverse. This term generally refers to three-phase devices.

Tangent Errors: The electrical error (accuracy) of each individual cycle of a multispeed synchro or resolver.

Torque Synchro: A synchro that transmits or receives angular information while supplying a small amount of motive power.

Transformation Ratio: The ratio of output voltage to input voltage, usually referred to as TR.

Transmitter: A synchro with one input phase and three output phases electrically 120 degrees apart. This type of device transmits signals to a receiver proportional to rotor position.

Transolver: A hybrid synchro with a three-phase stator and a two-phase rotor. This type of device can be used in either direction as a control transmitter or a control transformer.

Variable Reluctance Unit: A brushless synchro or resolver in which both the input and the output windings are on the stator (the outer element), with none on the rotor. Units of this type will always be multispeeds. Single speeds are impractical.

APPENDIX A

MULTISPEED SYNCHRO AND RESOLVER RATIOS

SPEED	Nx	1-Nx	VR	B/L
1	A	—	N	A
2	A	N	A	A
3	A	N	A	A
4	A	A	A	A
5	A	P	P	A
6	A	A	A	A
7	A	P	P	P
8	A	A	A	A
9	A	A	P	P
10	A	A	P	A
11	A	A	—	P
12	A	A	A	P
15	A	A	P	P
16	A	A	P	A
18	A	A	P	A
20	A	A	P	P
24	A	A	P	P
25	A	A	P	P
27	P	P	A	P
30	A	A	P	P
32	A	A	P	A
36	A	A	A	A
40	A	A	P	P
64	A	A	A	A
72	A	A	P	P
96	A	A	P	P
128	A	A	P	P
150	A	A	P	P
<i>Note: Fractional speeds for limited rotation are also available, such as a 4/5-speed.</i>				

Legend:

Nx — Multispeed only
 1-Nx — One- and Multispeed
 VR — Variable Reluctance
 B/L — Brushless

A — Available
 P — Possible
 N — Not Practical

APPENDIX B

BINARY TO ANGULAR CONVERSIONS

BINARY BITS (N)	DEGREES /BIT	MINUTES /BIT	SECONDS /BIT	MILLI-RADIANS	ANGULAR MILS	RESOLUTION (2 ^N)
0	360.0	21600.0	1296000.0	6283.1853	6400.0	1
1	180.0	10800.0	648000.0	3141.5927	3200.0	2
2	90.0	5400.0	324000.0	1570.7963	1600.0	4
3	45.0	2700.0	162000.0	785.3982	800.0	8
4	22.5	1350.0	81000.0	392.6991	400.0	16
5	11.25	675.0	40500.0	196.3495	200.0	32
6	5.625	337.5	20250.0	98.1748	100.0	64
7	2.8125	168.75	10125.0	49.0874	50.0	128
8	1.40625	84.375	5062.5	24.5437	25.0	256
9	0.703125	42.1875	2531.25	12.27184	12.5	512
10	0.3515625	21.09375	1265.625	6.13592	6.25	1024
11	0.1757813	10.546875	632.8125	3.06796	3.125	2048
12	0.0878906	5.273438	316.40625	1.53398	1.5625	4096
13	0.0439453	2.636719	158.20313	0.76699	0.78125	8192
14	0.0219727	1.318359	79.10156	0.38350	0.390625	16384
15	0.0109836	0.659180	39.55078	0.19175	0.1953125	32768
16	0.0054932	0.329590	19.77539	0.09587	0.0976563	65536
17	0.0027466	0.164795	9.88770	0.04794	0.0488281	131072
18	0.0013733	0.082397	4.94385	0.02397	0.0244141	262144
19	0.0006886	0.041199	2.47192	0.01198	0.0122070	524288
20	0.0003433	0.020599	1.23596	0.00599	0.0061035	1048576
21	0.0001717	0.010300	0.61798	0.00300	0.0030518	2097152
22	0.0000858	0.005150	0.30899	0.00150	0.0015259	4194304
23	0.0000429	0.002575	0.15450	0.00075	0.0007629	8388608
24	0.0000215	0.001287	0.07725	0.00037	0.0003815	16777216

1 Radian = 57.29577951 Degrees
 1 Angular Mil = 0.05625 Degree
 1 Angular Mil = 3.375 Arc Minutes

1 Degree = 0.017453292
 1 Degree = 17.453292 Milliradian
 1 Degree = 17.77778 Angular Mils