# Chapter III

# Synchro and Resolver to Digital Conversion

* synchro is a 3 wire input.
* Resolver is a 4 wire input.

## INTRODUCTION

### Function of SDC's and RDC's

The function of the Synchro to digital and the Resolver to digital converter is, as the name suggests, to convert three-wire synchro or four-wire resolver information into digital format.

The most common code for the digital output is natural binary and the word lengths range from 10 to 18 bits. A description of natural binary code and other codes encountered in the converters is found in chapter 2.

The very high M.T.B.F's of synchros and resolvers (see chapter I) and the associated converters make this system of digital angular transducing the most reliable and cost effective available.

### Types of SDC and RDC

There are predominantly two types of converter available, viz,

(a) Tracking

(b) Successive approximation

These two types of converter work on totally different principles and are usually used for different applications. It is very important to recognise the advantages and disadvantages of each type.

In the successive approximation converter, the resolver format signal (all converters whether successive approximation or tracking work internally on resolver as opposed to synchro format signals — see chapter II) is sampled at the peak of the reference waveform by sample and hold amplifiers to provide two D.C. voltages ie.

$$V \sin\theta$$
$$\text{and} \quad V \cos\theta$$

These voltages are then processed by the converter to derive a digital representation of angle $\theta$, by a method similar to that used in a successive approximation analog to digital converter.

Successive approximation converters are often used where a large number of channels of synchro or resolver information have to be converted, the analog information from each channel being held on sample and hold amplifiers prior to conversion. A system of multiplexing is used to switch the sample and hold outputs into the central converter when required. A very basic dual channel successive approximation system is shown in Fig. 3-1 and a more detailed description is given at the end of this chapter.

The main disadvantage of a successive approximation converter is that the synchro or resolver data has to be held by the sample and hold amplifiers at the peak of the reference waveform. Therefore in a 400 Hz system, a maximum wait of 2.5 mS will be required before this condition arises in addition to the actual conversion time which can be around 75 microseconds.

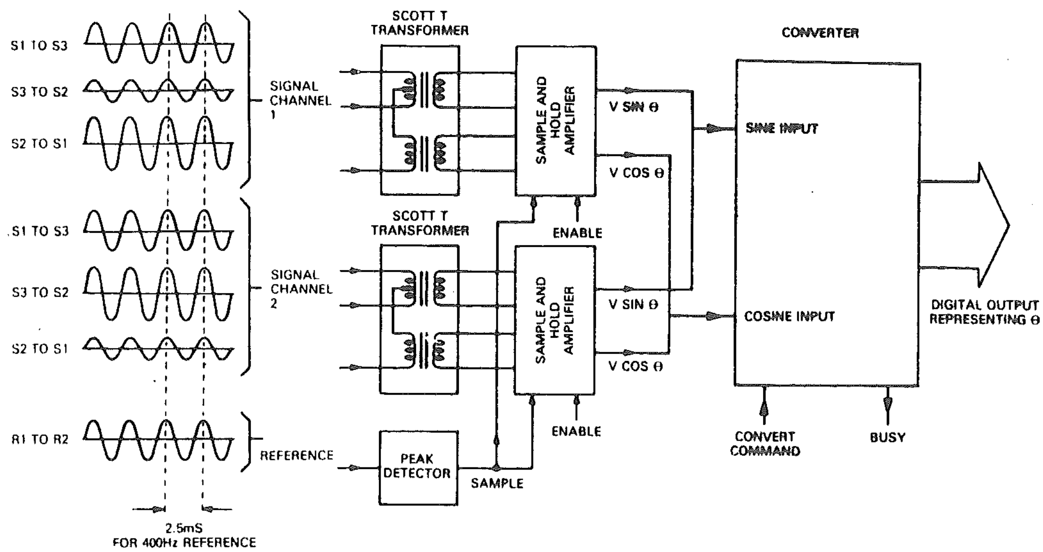


**Fig. 3-1** A simple dual channel successive approximation synchro to digital converter system.

Suppose that the input data is changing at the rate of 1 revolution per second and the fortunate situation arises such that the system is instructed to sample and convert just at the time that a peak of the reference waveform occurs. The data will therefore be present 75 microseconds later. By the time the data is available and the 75 microseconds has elapsed, the actual input angle will have changed by:

$$\frac{75}{1000000} \times 360° = 1.62 \text{ Arc. Mins.}$$

However, suppose that the system is instructed to convert at the instant before the reference peak is present, in which case the voltages held on the sample and hold amplifiers will not have been updated for approaching 2.5 mS, the digital representation of the angle will be stale by:-

$$2.5 \text{ mS} + 75\ \mu\text{S} = 2.575 \text{ mS}$$

In this case therefore, before the digital data is available, the shaft has turned through an angle of:-

$$\frac{2.575}{1000} \times 360° = 55.6 \text{ Arc. Mins.}$$

This example illustrates that with this type of converter a *stale data problem is inevitable.*

The problem is compounded when a number of channels of synchro or resolver data have to be converted.

Another problem of the successive approximation converter is its lack of noise immunity. Any noise which alters the ratio of the resolver format voltages will cause errors, since it is the tangent of the ratio of the voltages which the converter uses. Noise interference is often of a spiky nature and although any spikes occurring at other times than the sampling time will have no effect, those caught by the sampling window will have a direct effect on the accuracy of the output.

For example, a spike of amplitude equal to 10% of the input line to line voltage will give rise to errors of:

$$\text{Tan}\theta - \frac{.1 + \text{Sin}\theta}{.1 + \text{Cos}\theta}$$

These spikes will therefore have no effect at 45° but will have a large effect at 0° and equivalent angles.

It should be understood that as with tracking converters, noise on the original reference waveform is of no consequence since the noise will be resolved in the same way as the signal.

The problems of successive approximation converters described above are overcome in tracking converters.

The tracking device is the most versatile, problem free and commonly used type of synchro or resolver to digital converter available and a study of its principles, advantages, specifications and applications will occupy the majority of this chapter.

## TRACKING SYNCHRO AND RESOLVER TO DIGITAL CONVERTERS

### Principles of the tracking converter

A tracking converter is in fact a complete electronic type 2 servo loop and its operation is explained below.

However it is important first to explain that the only difference between a tracking synchro to digital converter and a tracking resolver to digital converter is in the configuration of the input transformers. There is no other difference apart from this.

A synchro to digital converter is shown in Fig. 3-2 below.

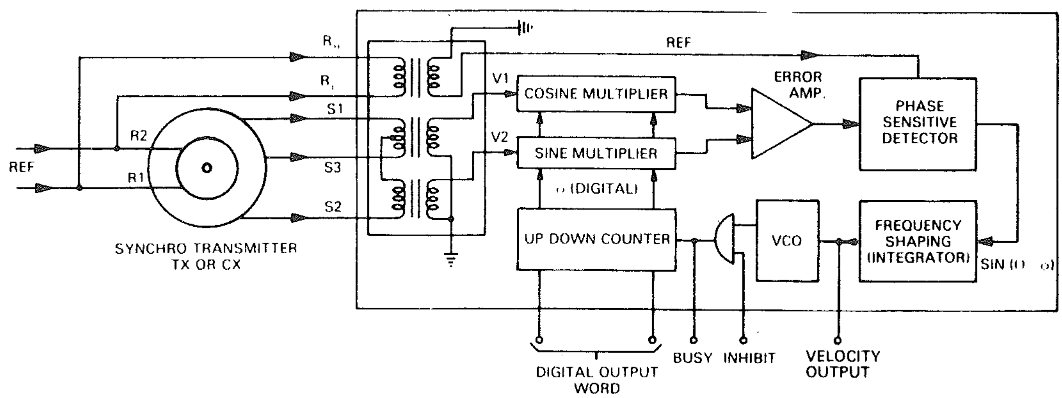


**Fig. 3-2** A tracking synchro to digital converter.

The S1, S2 and S3 terminals of the synchro control transmitter or the torque transmitter are connected to the S1, S2 and S3 inputs of the converter. A Scott connected transformer pair (see chapter II) then converts the synchro format information into resolver format as well as performing a step down voltage function in order to provide more workable voltages for the circuitry.

The resolver format signals from the resolver transmitter are fed into totally separate transformers for the Sine and Cosine channels, which apart from providing isolation also perform the step down voltage function.

In both SDC's and RDC's the converter works internally with resolver format voltages.

To understand the conversion process we can refer to either Fig. 3-2 or Fig. 3-3.

The Sine and Cosine multipliers are in fact multiplying digital to analog converters which incorporate sine and cosine laws.

Let us assume that the current state of the up-down counter is at angle $\phi$. The resolver format voltages on the outputs of the transformers are:

$$V_1 = V\sin\omega t \, \sin\theta$$

$$\text{and} \quad V_2 = V\sin\omega t \, \cos\theta$$

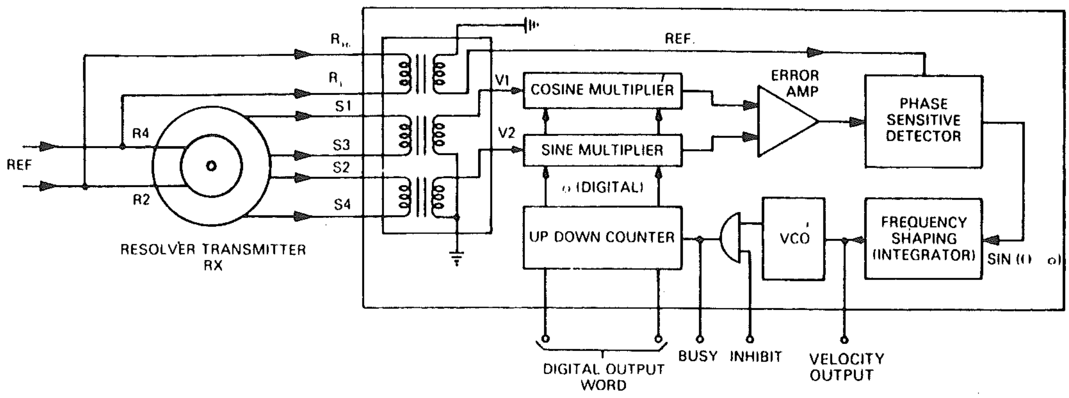


**Fig. 3-3** A tracking resolver to digital converter.

where $\theta$ is the angle of the synchro or resolver shaft. The digital angle $\phi$ is applied to the Cosine multiplier and multiplied by $V_1$ to produce:

$$V \operatorname{Sin} \omega t \operatorname{Sin} \theta \operatorname{Cos} \phi$$

Digital angle $\phi$ is also applied to the sine multiplier and multiplied by $V_2$ to produce:

$$V \operatorname{Sin} \omega t \operatorname{Cos} \theta \operatorname{Sin} \phi$$

These signals are subtacted by the error amplifier to give the error signal which is:

$$V \operatorname{Sin} \omega t (\operatorname{Sin} \theta \operatorname{Cos} \phi - \operatorname{Cos} \theta \operatorname{Sin} \phi)$$

A simple trigonometrical relationship shows this to be:

$$V \operatorname{Sin} \omega t \operatorname{Sin} (\theta - \phi)$$

This A.C. error signal is then demodulated by the phase sensitive detector which utilises the system reference voltage. A D.C. error signal is therefore produced which is proportional to:

$$\operatorname{Sin} (\theta - \phi)$$

This error signal is then fed into an integrator, the output of which drives a voltage controlled oscillator (V.C.O.). The V.C.O. outputs pulses to the up-down counter until:

$$\operatorname{Sin} (\theta - \phi) = 0$$

At this point

$$\theta - \phi = 0$$

or

$$\theta = \phi$$

Therefore the internal loop will null with the up-down counter and hence the digital output representing angle $\theta$.

The important thing to remember about a tracking converter is that the output digital word automatically follows the input *without having to be given any external convert command instructions*, ie. the converter follows or "tracks" the input. If the input is not changing the converter is nulled and doing nothing. If the input is changing, the output word automatically updates every time that the input increments through an angle equivalent to the weight of the Least Significant Bit (L.S.B.).

For example, if the unit is a 12 bit converter, the output counter will be updated 4096 ($2^{12}$) times per 360° input change or every:

$$\frac{360}{4096} = 5.3 \text{ Arc. Mins.}$$

* 12 Bit

*Comparison with a mechanical servo system*

The inclusion of the integrator in the tracking converter circuit makes the system into a type 2 servo loop. Type 2 loops are characterised by having a zero error signal for a constant velocity or a stationary input. The error signal is present only during periods of acceleration or deceleration. The similarity between the electromechanical type 2 servo loop and the tracking converter loop is illustrated in Fig 3-4.

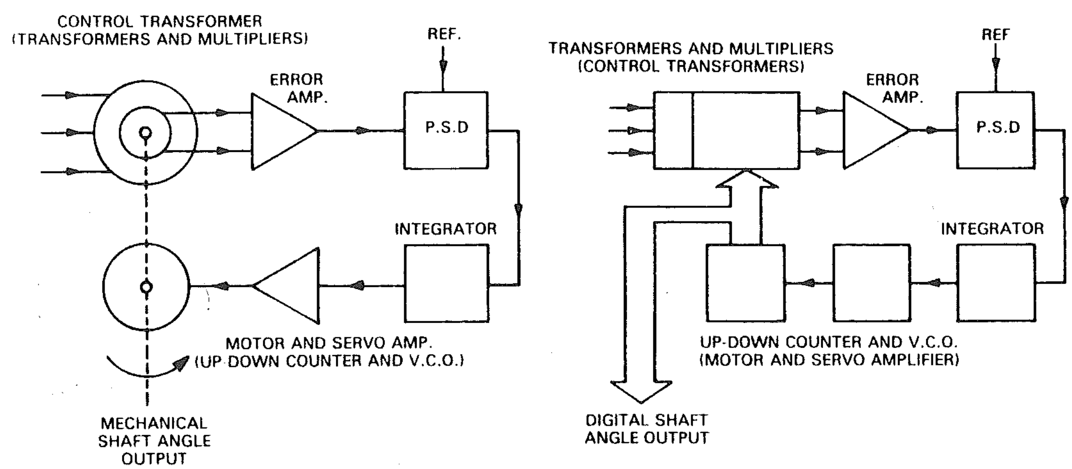


**Fig. 3-4** The analogy between the tracking converter and an electromechanical type 2 servo loop.

## Advantages of a tracking converter

*Ratiometric operation*

The two dominant methods of synchro and resolver to digital conversion, ie. tracking and successive approximation are both ratiometric techniques. With both methods, the basic conversion is dependent upon the ratio of the resolver format voltages being equal to the tangent of the shaft angle.

Alternative methods of conversion are sometimes used which make use of analog to digital conversion together with digital Sine and Cosine look-up tables. For such methods to be satisfactory, it is necessary that the individual amplitudes of the Sine and Cosine voltages are very precisely controlled, such systems sometimes use $V^2 \sin^2 \theta + V^2 \cos^2 \theta = V^2$ together with an auxilliary loop to compare $V^2$ with a reference. These methods are more complicated and less accurate than the Sine and Cosine multiplier method used in the tracking converters which are intrinsically ratiometric.

The operation of the tracking converter is therefore not dependent on the absolute magnitudes of the signal input but on the ratio between the signals. For this reason, any voltage drops along the lines from the synchro or resolver to the converter are relatively unimportant providing that usable voltages are available at the converter. This means that long lines from the transducer to the converter can be tolerated.

Another advantage that the ratiometric principle gives is tolerance of signal and reference waveform shape. The units are not particularly susceptible to harmonic distortion on the signal and the reference and can in fact be operated on square wave or triangular wave references provided that this is acceptable to the synchro or resolver. (See appendix C for a detailed discussion on harmonic distortion.)

*Noise immunity*
Because the error signal in a tracking converter is integrated, the device provides a high degree of noise immunity. Spikes occurring at any time will contribute to the error but if they are of short duration they will have less effect. A very important point concerning this matter is that it is the net area of the spike which produces errors and with inductively coupled spikes the positive and negative areas are equal. It is this fact which makes the tracking converter tolerant of noisy signals. Once again the noise immunity is a big advantage where it is required to place the converter at a distance from the synchro or resolver or transmit angular information through a noisy environment where digital transmission would not be possible. An example of this is shown in Fig. 3-5 where a synchro is taking the turning information from a radar antenna and transmitting it to a tracking synchro to digital converter in the radar office without the possibility of corruption by microwave radiation.

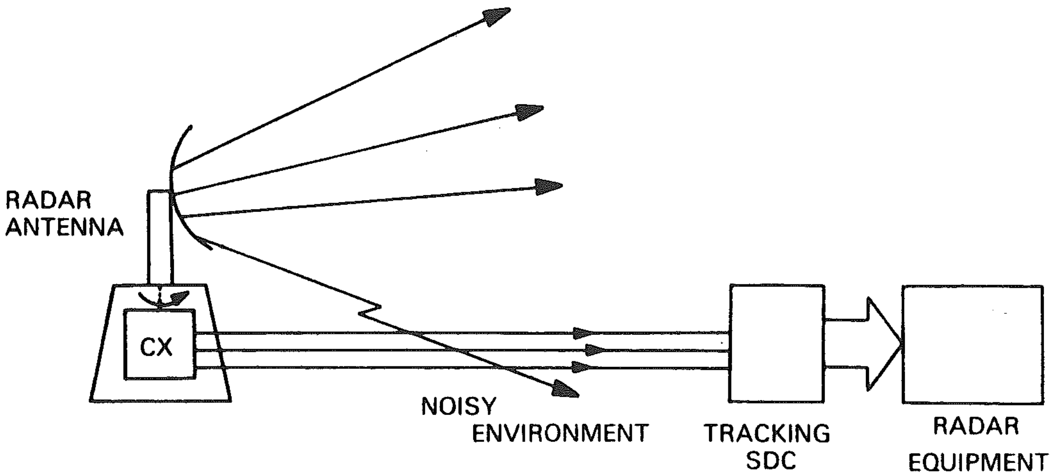


**Fig. 3-5** Transmitting angular information through noisy environments with a tracking converter.

*Instant digital data*
The digital data provided by a tracking converter is always fresh and available for use. Because the output always automatically follows the input, it does not suffer from any of the stale data problems of successive approximation converters. In the latest tracking converters, for example the hybrid types SDC1741 and SDC1742 and the modular SDC1725 and SDC1726, the outputs are latched and also Three-state making data transfer very simple. (See section "Data transfer" later in this chapter.)

*Velocity voltage outputs*
The design of the tracking converter means that the input to the Voltage Controlled Oscillator (V.C.O.) is a D.C. voltage representing the input velocity. This voltage is sometimes made available and can often be used in an associated servo system. More information on the velocity voltage output and its application is given later in this chapter in the section "Velocity voltage outputs from tracking converters".

**Tracking converter packaging**

Tracking synchro or resolver to digital converters normally come as Hybrid integrated circuits or Modules.

*Modules*
The older style modular tracking converters were a standard size of 3.125 × 2.625 × 0.8 inches (79.4 × 66.7 × 20.4 mm). These converters often required external transformers for 60 Hz operation, the transformers being approximately half the size of the module.

Advances in technology and the development of microtransformers made it possible to reduce the profile height to 0.4 inches while at the same time including the transformers within the module.

The very latest modular converters have internal transformers, which are capable of working from 50 Hz to 10 KHz, incorporated in a converter profile height of 0.35 inches (8.9 mm). This makes it possible to use these converters in a rack where the spacing of the printed circuit boards is 0.5 inches. A photograph of a 0.35 inch profile height converter is shown in Fig. 3-6

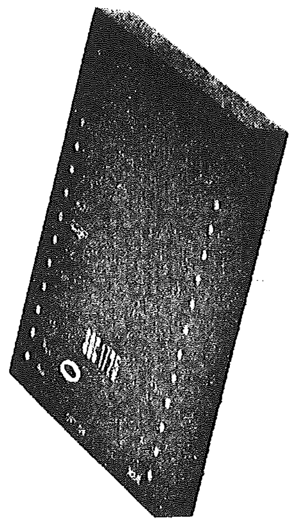

**Fig. 3-6** A 0.35 inch profile height tracking synchro to digital converter (SDC1725).

The modules are potted using automatic equipment with Dow Corning SYLGARD 170 which has excellent thermal conductivity properties.

The case and header plate of the modules are moulded from Diallyl phthalate which is a plastic material capable of withstanding high temperatures.

The connections to modular converters are normally by 0.040 inch diameter gold plated brass pins which can be used with individual pin sockets or soldered directly into the board.

*Hybrid converters*

Advances in transformer and semiconductor technology have now led to the development of Hybrid integrated circuit tracking converters with *internal transformers* for example the SDC1741 and SDC1742. Previously hybrid converters had been available but only with internal electronic Scott T inputs and not with internally packaged true transformer isolation.

These recently introduced devices are already having a great impact in applications such as avionic equipment where modules are sometimes unsuitable because of size and discrete component successive approximation converters suffer from the usual stale data and noise problems. The overall package size of these hybrid devices is 1.74×1.14×0.26 inches (44.2×28.9×6.6 mm).

A hybrid converter of this type is shown in the photograph in Fig. 3-7.

Size is not the only advantage that hybrid converters have over the modular devices. Firstly, they are capable of working at higher operating temperatures than the modules (125°C) and secondly their construction and low chip count provides them with a very high M.T.B.F. (Mean Time Between Failures) as well as a compliance with most of the High Rel. integrated circuit specification requirements encountered in the Military and Aerospace fields.

## Connecting and using a tracking converter

A tracking synchro or resolver to digital converter is very simple to use, so simple in fact that if the signal and reference from the synchro or resolver system are connected correctly to the converter, the digital output will track to the shaft angle within a few milliseconds of the power supplies being applied. A tracking synchro to digital converter (14 bit) is shown connected correctly to a synchro in Fig. 3-8 and a resolver to digital converter is shown connected to a resolver in Fig. 3-9.

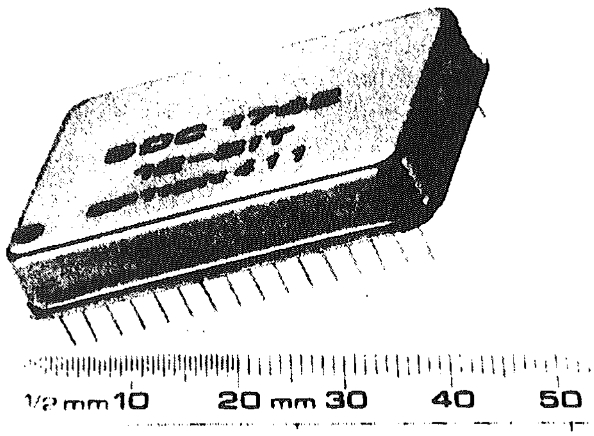


**Fig. 3-7** SDC1742 Hybrid tracking converter with internal transformers.

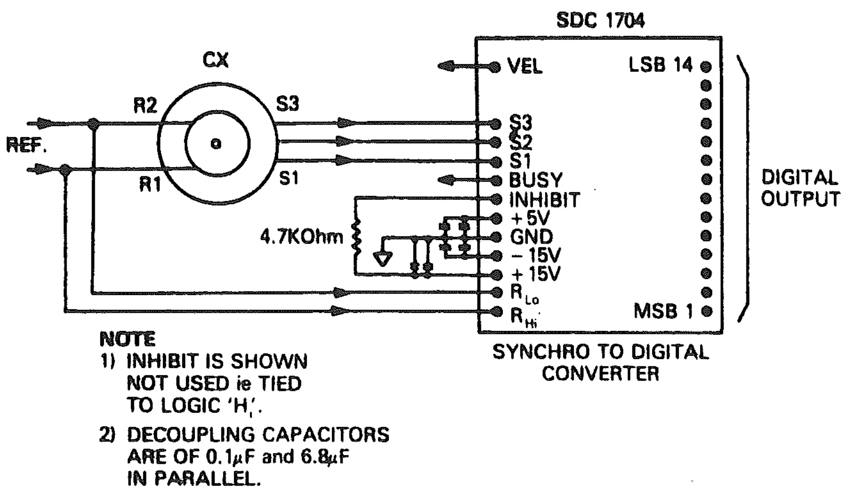


**Fig. 3-8** A tracking synchro converter connected to a synchro transmitter.

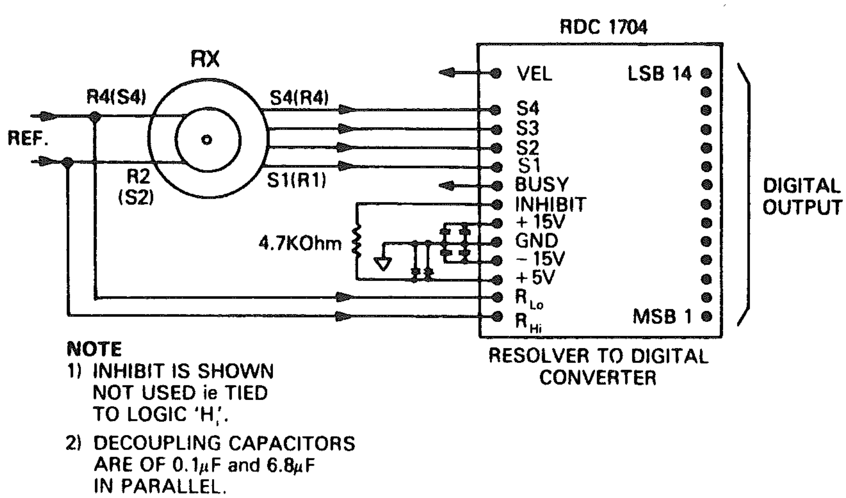


**Fig. 3-9** A tracking resolver converter connected to a resolver transmitter.

Although tracking converters are very simple to use, certain questions often arise and some of these are answered below.

*Connecting the synchro or resolver inputs*

1) In the case of a synchro to digital converter the S1, S2 and S3 terminals should be

joined to the corresponding S1, S2 and S3 inputs on the converter.

2) In the case of a resolver to digital converter where the rotor is energised, S1, S2, S3 and S4 on the resolver should be connected to the corresponding inputs on the converter. If the stator of the resolver is energised, then R1 on the resolver should be connected to S1 on the converter, R2 to S2, R3 to S3 and R4 to S4.

3) The system reference should be connected to $R_{Hi}$ and $R_{Lo}$ on the converter. The convention regarding the correct phase relationship between the signal and the reference waveforms is given in chapter 2. If the reference is connected the wrong way round, ie. the connections to $R_{Hi}$ and $R_{Lo}$ are reversed, the digital output will be 180 degrees in error although no damage will result.

4) If the connections to S1 and S3 are reversed on a synchro converter, the digital output will track in the opposite direction to the input.

5) For distances up to 20 feet, the connection between the synchro or resolver and the converter can be made with ordinary wire preferably twisted. For greater distances than this it is best to use individually screened multicore low capacitive cable. (It is not unknown for synchro information to have been transmitted over 2 Kilometres using this type of cable.)

6) No damage will result to a converter if either the signal or the reference is present without the D.C. power rails being connected. Conversely, no damage will result to a tracking converter if the D.C. power supplies are present with no signal or reference inputs.

7) It should be ensured that the converter is the correct option as far as signal and reference voltage are concerned. Most tracking converters can be externally resistively scaled to cater for higher voltages than that for which a particular converter is intended. See section on "Tracking converter terminology and definitions" headings 'Reference voltage' and 'Signal voltage' later in this chapter.

8) Any reference frequency can be applied to the latest generation of modular low profile and hybrid tracking converters without damage resulting as long as the signal and reference voltage limits for the particular converter are not exceeded. However there is no guarantee that the converter will function correctly. See section "Tracking converter terminology and definitions" heading 'Reference and signal frequency' in this chapter.

9) It is advisable that the signal and reference voltages should not be routed through the same wiring looms as the power supplies and digital data.

*Connecting the power supplies*
The D.C. power supplies should be connected as per the appropriate data sheets. The positive and negative supplies should under no circumstances be reversed and the levels should be kept to within ±5% of the nominal voltage.

Decoupling capacitors of value 0.1μF and 6.8μF should be connected in parallel, as near the converter as possible, from the power supply pins to GND. See also section in this chapter "Tracking converter terminology and definitions" heading 'Power supplies'.

*Connecting the digital inputs and outputs*
The function of the BUSY and INHIBIT connections is discussed in this chapter in the section "Data transfer". However key things to remember are:

1) Connect the INHIBIT pin through a 4.7 K Ohm resistor to the +5 volt power rail if the facility is not going to be used.

2) If the converter has a Three-state output, connect the ENABLE pin to a logic 'Lo' state if the Three state facility is not going to be used.

3) The digital output leads should be kept as short as possible, preferably to less than 6 inches in all cases. However the subject of the distance which digital outputs can drive is a very complex one and depends on factors such as type of output logic device, capacitive coupling between the output leads and type of logic device acting as the receiving element. The output logic device type for all tracking converters discussed in this book is given in chapter II and this should be used in conjunction with the manufacturers literature on the logic device in question to assess the loading and driving capabilities. It is important to remember however that in most tracking converters a fraction of the driving capability of the output device is used by the converter internally and the load driving capability in the specifications is that which is available.

## Data Transfer

Tracking synchro and resolver to digital converters are usually used to interface with digital processors where the question of transferring the data on to data highways will arise.

When discussing data transfer, there are two types of tracking converter to be considered. These are:

(1) Tracking converters where the digital output is taken directly from the up-down counter. Examples of this are SDC1700, SDC1702, SDC1704, SDC1602, SDC1603, SDC1604, SBCD1752, SBCD1753, SBCD1756, SBCD1757.

(2) Tracking converters with latched Three-state outputs. Examples of this are SDC1725, SDC1726, SDC1741, SDC1742.

*Direct output tracking converters*

This type of converter takes the output digital word directly from the up-down counter. These are the most common type of tracking converter and are typified by the simplified system shown in Fig. 3-10.

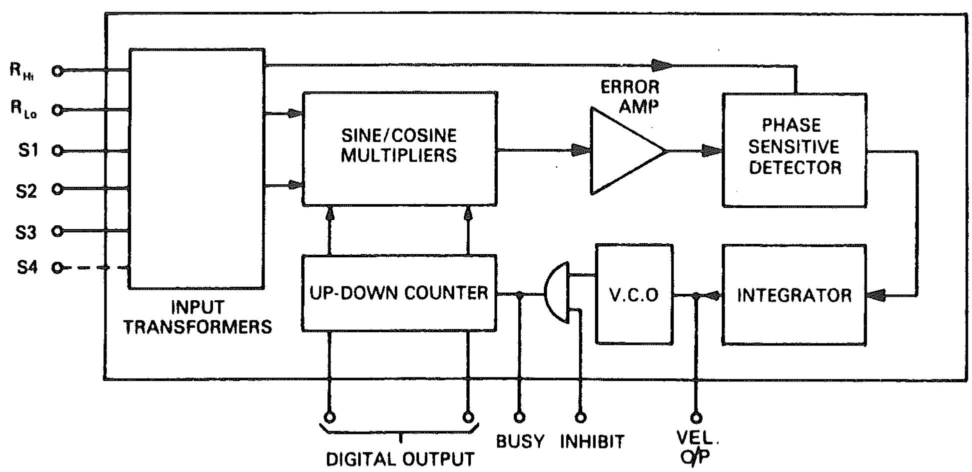


**Fig. 3-10** Simple functional diagram of a direct output tracking converter.

These converters have an external INHIBIT input facility which is 'AND'ed with the pulses from the V.C.O. The resultant pulses are used to update the up-down counter and are also brought out externally as BUSY pulses. The BUSY pulses are usually a few microseconds in width, and when they are in a logic 'Hi' state it means that the counter is being updated.

If the INHIBIT is taken to a logic 'Lo' state, the BUSY pulses will be unable to update the counter and the counter will be frozen with the last digital angle set in it. However, with the INHIBIT at a logic 'Lo' state, the V.C.O. pulses will be prevented from updating the counter and the internal converter tracking loop will have effectively been opened. If the INHIBIT is at a logic 'Hi' state the counter will be updated normally every time that the input changes by an angle equivalent to 1 Least Significant Bit.

There are therefore two basic ways to transfer data from this type of converter:

1) Detect when the BUSY output is at a logic 'Lo' state and transfer the data accordingly. See Fig. 3-11.

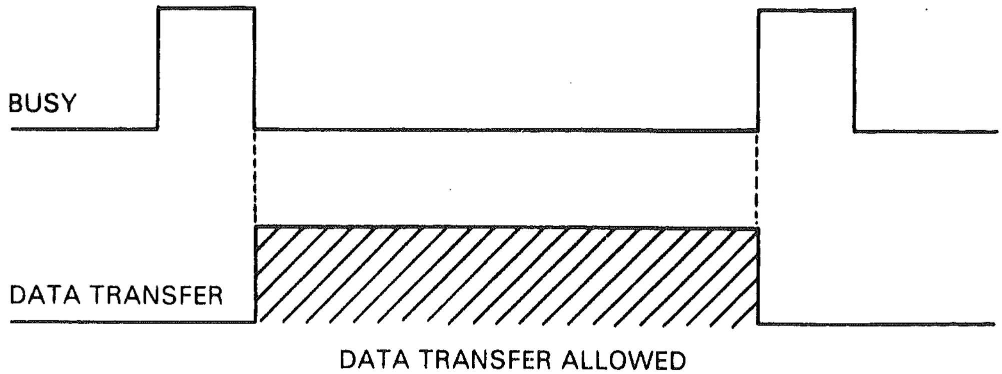


**Fig. 3-11** Data transfer using the BUSY pulse.

A question that often arises when transferring data by this method is 'What is the time between each BUSY pulse?'.

The answer to this is that no BUSY pulses are produced by the converter when the input is fixed and when the input is changing, the time between each BUSY pulse will depend on the speed of rotation of the input. For example, if the input of a 12 bit converter (4096 counts per 360°) is changing at 90°/Sec then the number of BUSY pulses occurring per second will be:

$$\frac{90}{360} \times 4096 = 1024$$

Therefore the time between the pulses will be 1/1024 = 0.976 mS

Similarly for a 360°/Sec input, the time between the pulses will be 244μS. These two cases are illustrated in Fig. 3-12.

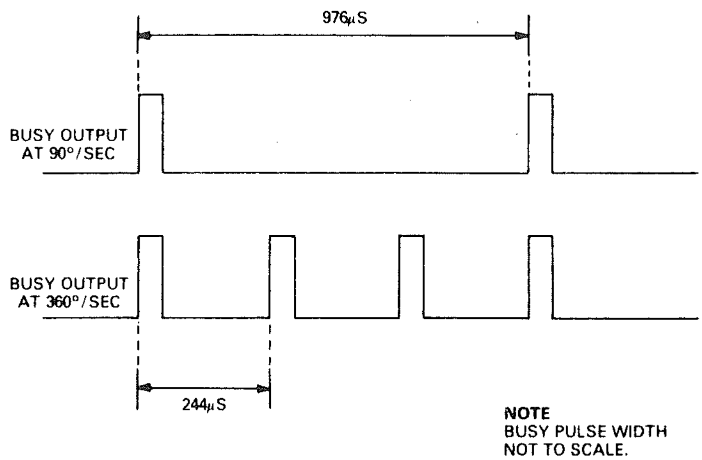


**Fig. 3-12** Time between BUSY pulses in a 12 bit converter for 90°/Sec and 360°/Sec inputs.

2) Take the INHIBIT to a logic 'Lo' state. Wait for at least the width of a BUSY pulse, transfer the data and immediately return the INHIBIT to a logic 'Hi' state. This method takes into account the fact that even if the INHIBIT is used during a BUSY pulse, the counter will be updated before the INHIBIT is effective. This part of the circuitry is not shown in the simplified diagram in Fig. 3-10. It is important in this method of transferring data that the INHIBIT is returned to a logic 'Hi' state before the next BUSY pulse arrives. If the INHIBIT is left at a logic 'Lo' state for any length of time the internal loop will have been opened and the converter will take a finite time to null when the INHIBIT is finally released. In this case, assuming that the up-down counter has missed at least one update pulse, the time which the converter will take to settle will depend on the difference between the input angle and up-down counter angle

at the time the INHIBIT is released. This difference in angle can be regarded as a step input and the corresponding settling times are shown in Figs. 3-29, 3-30 and 3-31.

This method of transferring data is shown in Fig. 3-13.

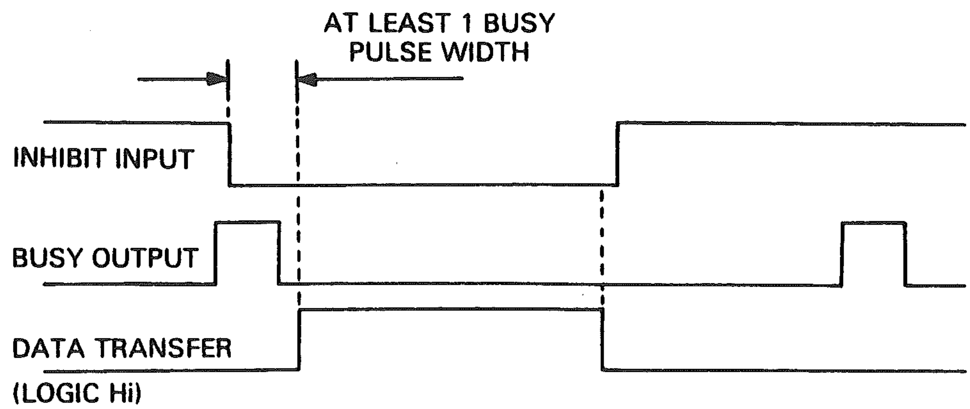


**Fig. 3-13** Data Transfer using the INHIBIT Input.

*Tracking Converters with latched Three-State outputs*

These converters function in exactly the same way as all other tracking converters. However, as can be seen from Fig. 3-14 the converter has latches and Three-State buffers following the up-down counter.

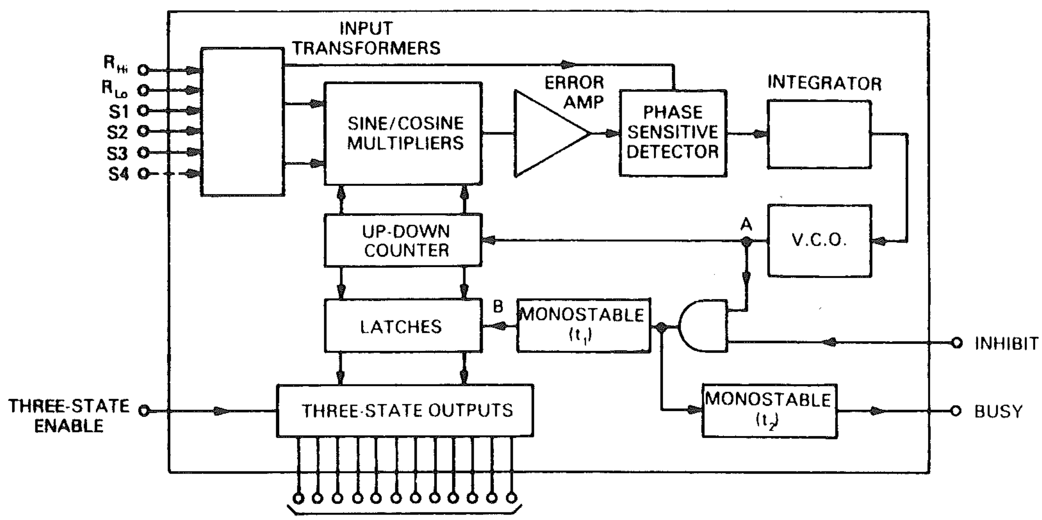


**Fig. 3-14** A Tracking Converter with latched Three-State outputs.

If the input to the converter is changing, the up-down counter is updated in the normal way and assuming that the INHIBIT is not applied, i.e. in a logic 'Hi' state, the latches will be updated in a time $t_1$ after this update. As soon as the up-down counter starts to be updated, the BUSY goes to a logic 'Hi' state and remains so for a time $t_2$. This time is sufficient to allow the up-down counter to be incremented and the data to be transferred into the latches.

As stated earlier, in the converter without latches, the use of the INHIBIT can open the converter loop. The essential difference between the latched Three-State output converters and the direct output converters is that the application of the INHIBIT *does not interfere with the internal converter loop* no matter how frequently it is applied or even how long it is left in the logic 'Lo' state. In fact it is possible to leave the INHIBIT in a logic 'Lo' state for an indefinite period without interfering with the internal converter loop, the output of the converter will return to the present input angle immediately the INHIBIT is released.

The simplest way to transfer data from a Three-State latched output converter is to apply the INHIBIT and wait for the time $t_2$ (see appropriate data sheet). *After this time, assuming that the Three-State ENABLE is at a logic 'Lo' state, the data on the output will represent* *the input angular position at the time the INHIBIT was applied.* This data will remain fixed on the output pins until the INHIBIT is removed. Meanwhile, the internal converter loop keeps updating the up-down counter.

When the INHIBIT is removed the internal latches will be updated immediately with the new counter information. The latches do not have to wait for a V.C.O. update pulse to occur. This feature of the circuitry is not shown in the simplified diagram in Fig. 3-14.

The BUSY pin can be used to indicate the state of the circuitry at any time. The ENABLE pin can be used at any time, a logic 'Lo' state causing the data to be presented to the outputs.

The timing of a Three-state latched output converter is shown in Fig. 3-15.

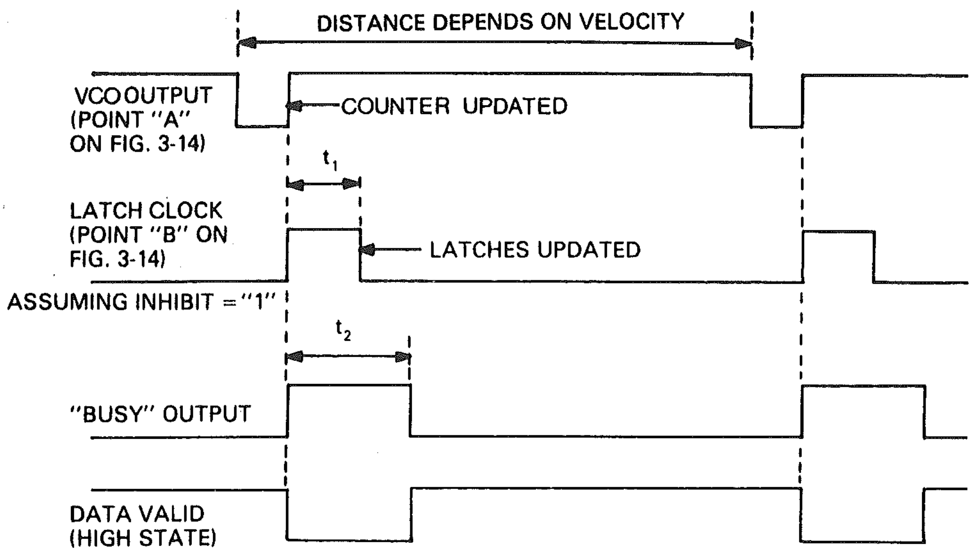


**Fig. 3-15** Three-state latched output converter timing diagram.

**Tracking converter terminology and definitions**

Below in alphabetical order is an explanation of many of the terms and parameters used in connection with tracking converters.

*Acceleration*

This parameter specifies the ability of the converter to withstand and track input accelerations.

The figure for acceleration sometimes quoted in the specification is given in terms of:

Degrees per second$^2$ for one additional L.S.B. of error.

This means that an acceleration of this value will cause the output angular position to lag behind the input angular position by a constant angle equivalent to 1 Least Significant Bit. eg. 1.32 Arc. Mins. in the case of a 14 bit converter. This error is in addition to the errors due to the converter's natural error curve.

A better way to specify the acceleration is by $K_a$ value. $K_a$ has the dimensions of $T^{-2}$ and is defined as:

$$\frac{\text{Input Acceleration}}{\text{Error in output angle}}$$

where the angular units used in the numerator and denominator are the same.

For example, if an acceleration of 20,000°/sec$^2$ gave an error lag. of 1 LSB in a 12 bit converter then

$$\text{Acceleration in LSB's} = \frac{20{,}000}{360} \times 4096\ \text{LSB/sec}^2$$

(There are 4096 counts or LSB's per 360° in a 12 bit converter).

Therefore

$$K_a = \frac{\dfrac{20{,}000 \times 4096}{360}}{1} = 227{,}555/\text{sec}^2$$

Once the $K_a$ value is known the acceleration is defined in any units. eg. in the above example the converter will give:

1 Arc Minute of additional error for an acceleration of 227,555 Arc Mins/sec$^2$

and 1 degree of additional error for an acceleration of 227,555°/sec$^2$

and so on.

However, the acceleration figure quoted in the tracking converter specification, whether it be as a $K_a$ value or as an acceleration in degrees per second$^2$ to give 1 L.S.B. of error, is *not* the maximum acceleration which the converter will stand. This maximum figure, which by necessity has to be stated in absolute terms is governed by the maximum allowable output swing of the internal error amplifier. If this maximum acceleration is exceeded then the digital output will irrecoverably lose track with the input. In general the maximum acceleration will be reached when the error between the input and the digital output is approximately 5 degrees. Therefore a tracking converter can withstand an acceleration in deg/sec$^2$ of about five times the $K_a$ value.

For example, take a converter with a $K_a$ value of 110,000/sec$^2$, the maximum acceleration will be about 600,000°/sec$^2$ or 1666 Revs/Sec$^2$.

Obviously, a converter will not be able to withstand the maximum acceleration for very long as it will soon reach its maximum tracking rate.

For example, in the case of the converter with the maximum acceleration of 600,000°/sec$^2$, suppose that it has a maximum tracking rate of 36 RPS. Therefore the maximum time for which the converter will be able to stand the maximum acceleration is:-

$$\frac{36 \times 360}{600{,}000} = 21.6 \text{ mS}$$

These tracking converter acceleration characteristics are particularly important in the machine tool control industry where, in the case of Inductosyns, very high accelerations are encountered.

*Accuracy*

This is the maximum error both positive and negative over a full 360° rotation. It is usually specified over the maximum operating temperature range and under the following conditions:

(a) ±10% signal and reference amplitude variation

(b) 10% signal and reference harmonic distortion

(c) ±5% power supply variation

(d) ±10% variation in reference frequency

The converter accuracy is normally checked dynamically over the 360° range during the manufacturing test phase. The equipment used is automatic test equipment which is calibrated against Singer Gertsch synchro/resolver standards. A typical error curve produced by the test equipment for a 12 bit tracking converter is shown in Fig. 3-16.

In actual fact, as can be seen from Fig. 3-16, two error curves are produced which are very slightly separated. One is for a rotation of 0 to 360° (the up count) and the other is for a rotation of 360° to 0° (the down count). The slight difference between the two curves is

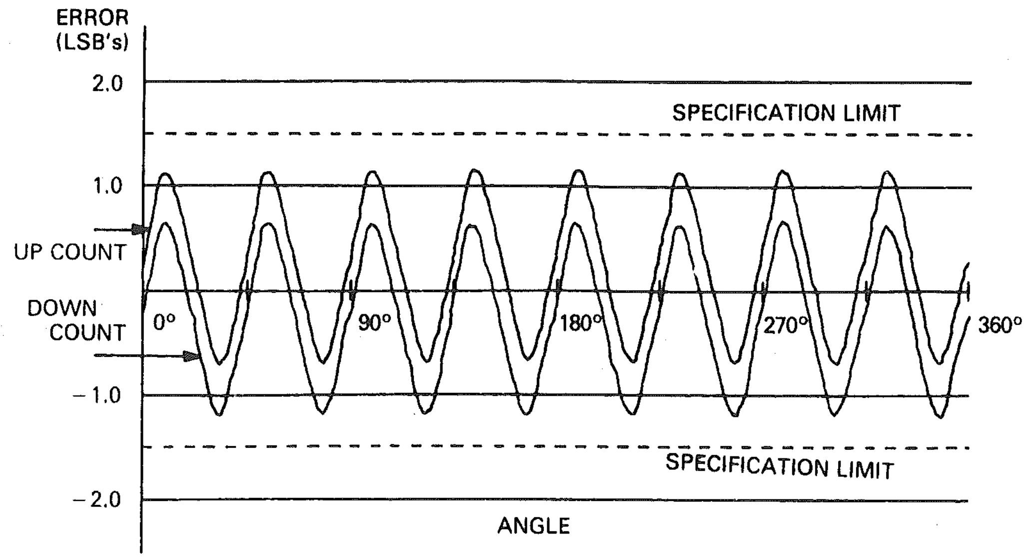


**Fig. 3-16** A test equipment error curve for a typical 12 bit tracking converter.

hysteresis which is deliberately introduced to eliminate any flicker problems which may otherwise occur. See heading 'Flicker' in this section.

*Bandwidth*
The bandwidth and frequency response of tracking converters are dealt with later in this chapter in the section "Bandwidth and transfer function of tracking converters".

*BUSY output*
As long as the INHIBIT is at a logic 'Hi' state, a BUSY pulse is produced on the BUSY output by all tracking converters when the up-down counter is updated. This pulse is usually positive going and between 0.5 $\mu$S and 9 $\mu$S in width. See section "Data transfer" in this chapter.

*Data output*
In converters where the output is a parallel word, the output coding is normally in natural binary or Binary coded decimal (B.C.D.). The output driving capability is given in the number of TTL loads that can be driven. Reference should be made to chapter II and also to the section in this chapter "Connecting and using a tracking converter" for details of the lead lengths that can be driven.

*Flicker*
This must not be confused with 'jitter'.

When the output bits change of their own accord while the input is fixed, or when the output word counts down when it should be counting up or vice versa, the converter is said to be flickering.

Flicker is a highly undesirable quality for a tracking converter to possess and very elaborate steps are taken in the design to eliminate it. One of these is the introduction of hysteresis into the error curve which is discussed in this section under the heading 'Accuracy'.

Some manufacturers state in their literature that their converters are 'Jitter free'. By our definition they mean that they are flicker free. (See heading in this section 'Jitter'.)

*Harmonic distortion*
The specification usually specifies the accuracy of a tracking converter with a limit of 10% harmonic distortion on the signal and reference waveforms. However, in practice as we have already stated, tracking converters can actually be used with square or triangular waveform references.

If an equal amount of harmonic distortion is present on both signal channels (when in resolver format) then the converter will operate satisfactorily. If the distortion is on one channel only then it will not.

A detailed discussion of the effect of harmonic distortion of the reference waveform is given in appendix C.

*INHIBIT*

The INHIBIT input is provided to assist data transfer. See section on "Data transfer" in this chapter.

*Jitter*

Jitter is not to be confused with flicker. Jitter is caused by the quadrature signals (signals at the reference frequency but 90° out of phase) from the synchro or resolver transmitter.

It is a condition in which for a constant input velocity, the output counter is not updated at perfectly regular intervals, i.e. each BUSY pulse arrives slightly before or slightly after it should do. This is illustrated in Fig. 3-17.

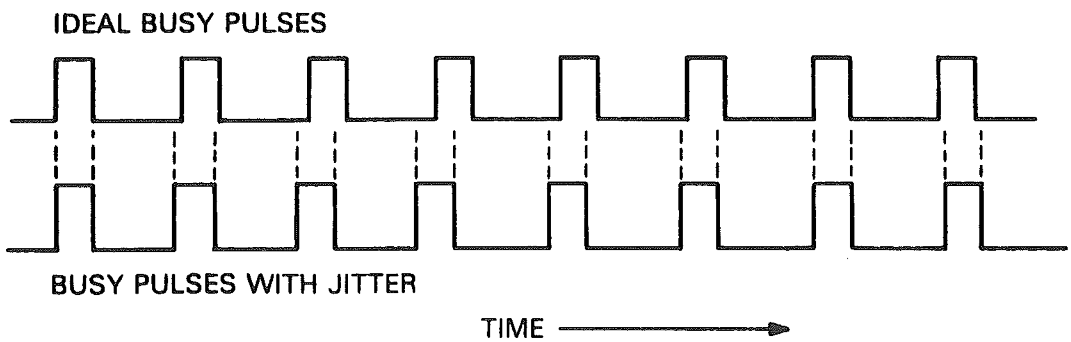


**Fig. 3-17** The effect of jitter on a tracking converter BUSY pulse or least significant bit.

As with flicker, the design of the converter is such that it tries to eliminate jitter. However, sometimes a compromise has to be made between the allowable jitter and the acceleration performance. Any jitter present in a tracking converter is included in the specified accuracy figure.

*Maximum data transfer time*

If the BUSY signal is to be used for data transfer purposes, transfer can take place as long as the BUSY signal is not present (i.e. in a logic 'Hi' state). Therefore, when the input is rotating, the time allowed for data transfer is the time between successive BUSY pulses. The method of calculating the time between BUSY pulses is given in the section on data transfer. See Fig. 3-18 and Fig. 3-12.

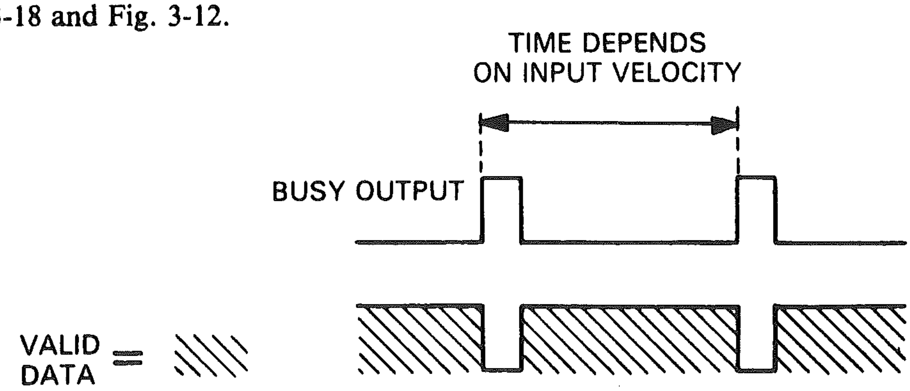


**Fig. 3-18** Data valid period of a tracking converter.

*Output Digital Word*

See 'Data Output' in this section.

*Phase Difference between Signal and Reference*
Synchro and Resolver transmitters introduce a phase difference between the reference and signal carrier waveforms. See Fig. 3-19.

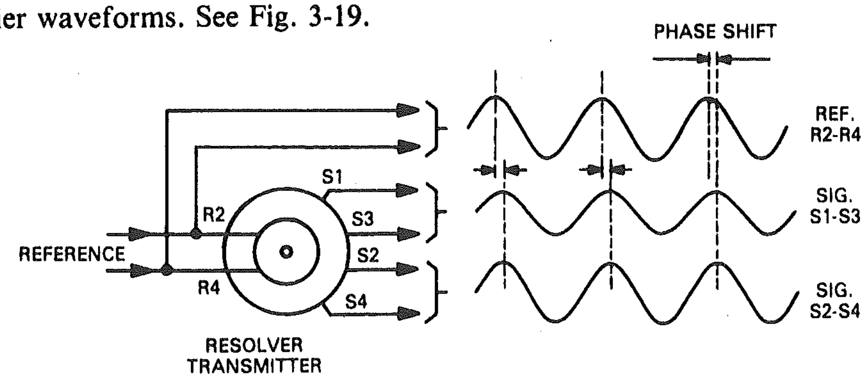


**Fig. 3-19** Phase Shift on the Output of a Resolver Transmitter.

This phase difference is normally in the order of a few degrees for standard CX's and RX's but can be as much as 60° with some slab resolvers. Most synchro and resolver converters can stand up to ±20° of phase shift before the accuracy is affected. If the phase shift is greater than this it can be reduced on the reference input by phase shifting circuitry.

There are however areas where the phase shift may be of some significance, for example when the input signals contain quadrature voltages in which case small errors may be caused. Quadrature voltages can be caused when the synchro or resolver rotation speed is a significant fraction of the reference frequency and also if the source CX has differential signal phase shifts. These questions are discussed fully in appendix D.

*Power Supplies*
The D.C. power supplies to the converter, which should be decoupled as closely as possible to the converter pins (see Figs. 3-8 and 3-9) do not have to be switched on in any particular order. In addition to this, no damage will be caused if the signal and reference supplies are present in the absence of the power supplies.

*Reference and Signal Frequency*
As stated in Chapter I, the most common synchro reference frequencies are 60 Hz and 400 Hz, and therefore synchro to digital tracking converters are manufactured to work at these two standard frequencies. Resolvers commonly operate from a 400 Hz or 2.6 KHz reference and therefore resolver to digital converters are manufactured to suit this frequency.

The higher the frequency, the better will be the dynamic performance which is achievable in the converter design. Thus for example a converter designed for 400 Hz will have much better dynamic performance than a converter designed for 60 Hz.

The accuracy of a tracking converter is normally guaranteed over a ±10% variation in the reference frequency for which the converter is intended. However in practice the latest designs of converter are fairly tolerant as far as reference frequency is concerned. These converters include:

| | |
|---|---|
| SDC1700 | 12 Bit Binary |
| SDC1702 | 10 Bit Binary |
| SDC1704 | 14 Bit Binary |
| SBCD1752 | 14 Bit B.C.D. |
| SBCD1753 | 14 Bit B.C.D. |
| SBCD1756 | 14 Bit B.C.D. |
| SBCD1757 | 14 Bit B.C.D. |
| SDC1725 | 12 Bit Binary, latched three-state |
| SDC1726 | 10 Bit Binary, latched three-state |
| SDC1741 | 10 Bit Binary, latched three-state, hybrid |
| SDC1742 | 12 Bit Binary, latched three-state, hybrid |

In general the above converters can be used at a frequency higher than that for which they are specified, although they will retain the dynamic performance (tracking rates, acceleration, and step response) characteristics of the basic converter. With the exception of the 60 Hz converters, which can be used at 50 Hz, the performance of the above converters will be unacceptable if they are used at a frequency lower than the 10% limit, although no damage will result.

Typical variation in accuracy with frequency for some of the converters mentioned above is shown in Figs. 3-20 thru 3-25 while the effect of harmonic distortion on the waveform is discussed under the harmonic distortion heading above and in appendix C.

*Reference Impedance*
This is normally between 200 and 300 KOhm in the case of high level references (115 volts r.m.s.) and between 20 and 60 KOhm in the case of low level references (26 volts r.m.s.). In the case of the converters mentioned under the *Reference frequency heading*, the input impedance is purely resistive.

*Reference Voltage*
The two basic reference voltages normally catered for in tracking converter designs are 115 volts r.m.s. and 26 volts r.m.s.. Although the accuracy of a converter is normally specified with a variation of ±10% in the reference voltage, most converters will allow the reference to drop by up to 50%. However, it should be stated that the performance and accuracy are not guaranteed under these conditions.

The converters listed under the heading *Reference frequency* can have the reference voltage input externally scaled by a resistor. This means that if a non standard reference voltage has to be catered for, a resistor can be added in series with the $R_{Hi}$ connection on a converter which is intended for a lower voltage. An example of this is shown in Fig. 3-26. In this example, a 60 volt reference is accommodated by using a 12 bit converter, type SDC1700, intended for a 26 volt reference. The method of calculating the resistor value is given in the appropriate data sheet.

*Resistive scaling*
See 'Reference Voltage' and 'Signal Voltage' headings in this section. Also see Section on "Connecting and Using a Tracking Converter" in this chapter.

*Resolution*
The resolution of a tracking converter is defined by the value of the Least significant bit (L.S.B.) and is therefore dependent on the word length of the digital output. The resolution of the most common word lengths is given below.

| *Word Length (Bits)* | *Resolution (Degrees)* | *Resolution (Arc. Mins)* | *Resolution (Arc. Mins/Secs)* |
|---|---|---|---|
| 10 | 0.35156 | 21.0936 | 21′ 5.6″ |
| 12 | 0.08790 | 5.2740 | 5′ 16.4″ |
| 14 | 0.02197 | 1.3182 | 1′ 19.1″ |
| 16 | 0.00549 | 0.3294 | 0′ 19.8″ |
| 18 | 0.00137 | 0.0822 | 0′ 4.9″ |

*Signal Impedance*
The signal input impedance of tracking SDC's and RDC's is normally about 200KOhm for High level (115 volt reference, 90 volt signal) systems and around 26 KOhm for low level (26 volt reference, 11.8 volt signal) systems. The tracking converter is a ratiometric device and therefore it is fundamental to the design that the signal input impedances are very accurately matched. ie. Impedance between S1 and S2 = S1 and S3 = S2 and S3 in the case of a synchro converter and impedance between S1 and S3 = S2 and S4 in the case of a resolver converter.

*Signal voltage*
The two common signal voltages catered for by tracking converters are 90 volts r.m.s. line to line max. which is mainly associated with 115 volt RMS reference voltage synchro systems and 11.8 volts r.m.s. line to line max. which is mainly associated with 26 volt r.m.s. synchro

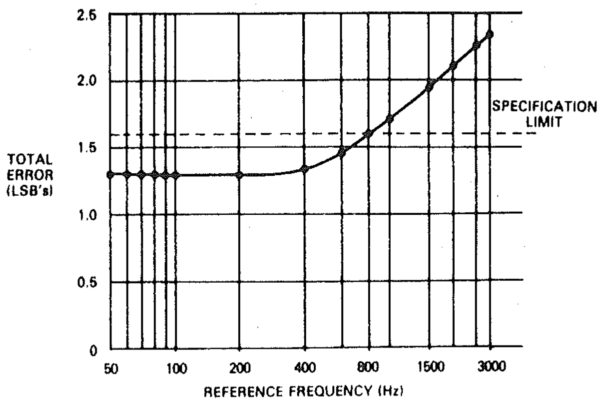


**Fig. 3-20** Accuracy vs. Frequency
SDC1700 60 Hz option

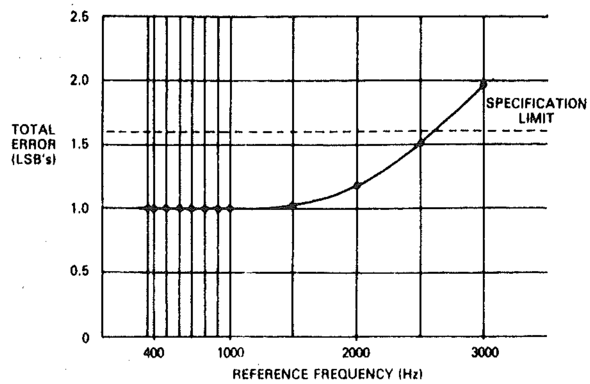


**Fig. 3-21** Accuracy vs. Frequency
SDC1700 400 Hz option

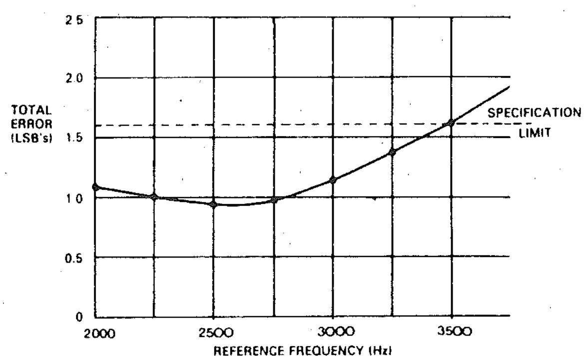


**Fig. 3-22** Accuracy vs. Frequency
SDC1700 2.6 Hz option

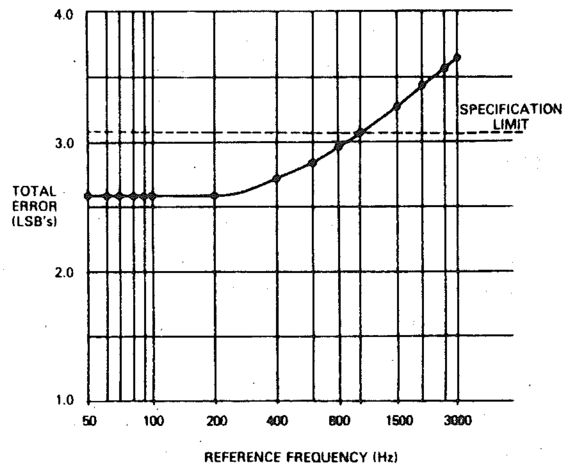


**Fig. 3-23** Accuracy vs. Frequency
SDC1704 60 Hz option

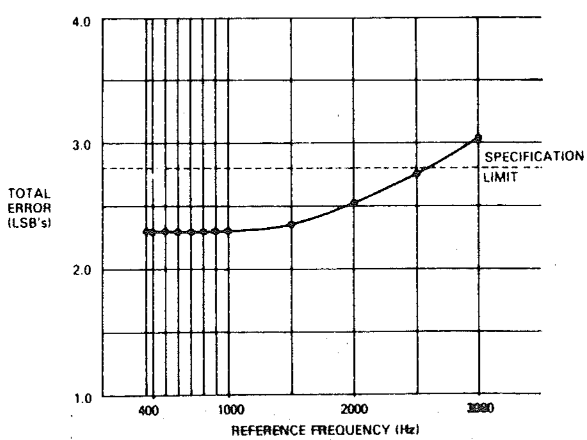


**Fig. 3-24** Accuracy vs. Frequency
SDC1704 400 Hz option

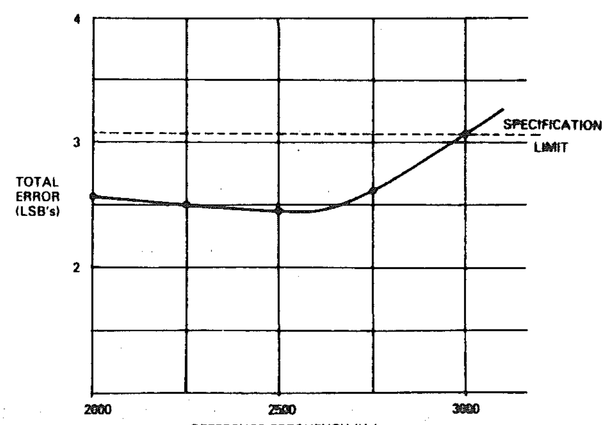


**Fig. 3-25** Accuracy vs. Frequency
SDC1704 2.6 KHz option

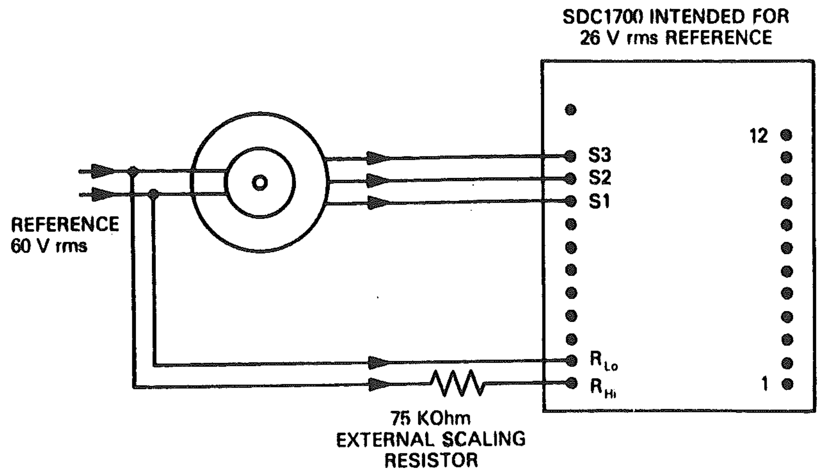


**Fig. 3-26** Resistive Scaling of the Reference voltage on SDC1700.

and resolver reference systems. However other voltages are catered for and the appropriate converter data sheet should be consulted.

The accuracy of a tracking converter is normally specified over a variation of ±10% in the signal voltage and outside these limits the performance cannot be guaranteed. Although the converter will continue to function, the effect of reducing the signal voltage below these limits will be to reduce the internal loop gain of the converter and so degrade the dynamic characteristics. In addition to this, the hysteresis gap between the up count and the down count of the error curve (see Fig. 3-16) will increase as the signal voltage is lowered and consequently the overall accuracy will be reduced. The exact amount of variation will depend on the converter type.

As far as increasing the signal voltage is concerned, an increase of greater than 10% will cause the internal converter amplifiers to limit and the converter will cease to function. However all converters where the input impedance is specified as being purely resistive can stand an increase of 50% in the signal voltage without causing damage.

In certain cases, particularly with resolvers, it is necessary to accommodate a signal voltage for which no standard tracking converter option exists. The converters where the input impedance is purely resistive can be resistively scaled to provide a solution to this problem. For example, if a resolver has a signal voltage of 19 volts r.m.s. line to line max. and the reference supply is 26 volts r.m.s., a resolver to digital converter having facilities for a 26 volt reference and an 11.8 volt signal can be used with external scaling resistors in the input lines S1 and S2. This is shown in Fig. 3-27.

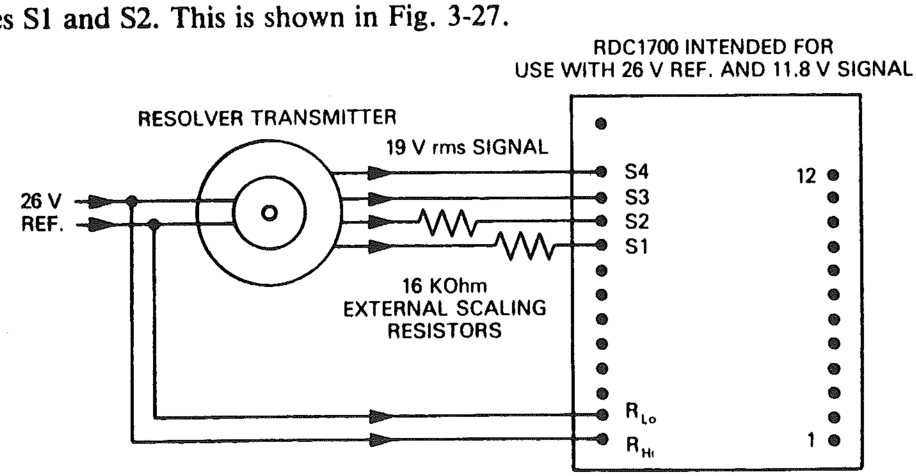


**Fig. 3-27** Resistively scaling the signal input to a resolver to digital converter.

The two resistors used in the above example will need to be closely matched in value and it is important that they should have equal temperature tracking characteristics. However, the absolute value of the resistors is not important as long as the voltage on the converter side of the resistors is within the 10% variation in signal voltage required by the accuracy specification of the converter.

A similar method can be used in the case of synchro converters to cater for non-standard voltages. For example in Fig. 3-28, a standard 90 volt signal unit is being used with a synchro where the signal voltage is 115 volts.

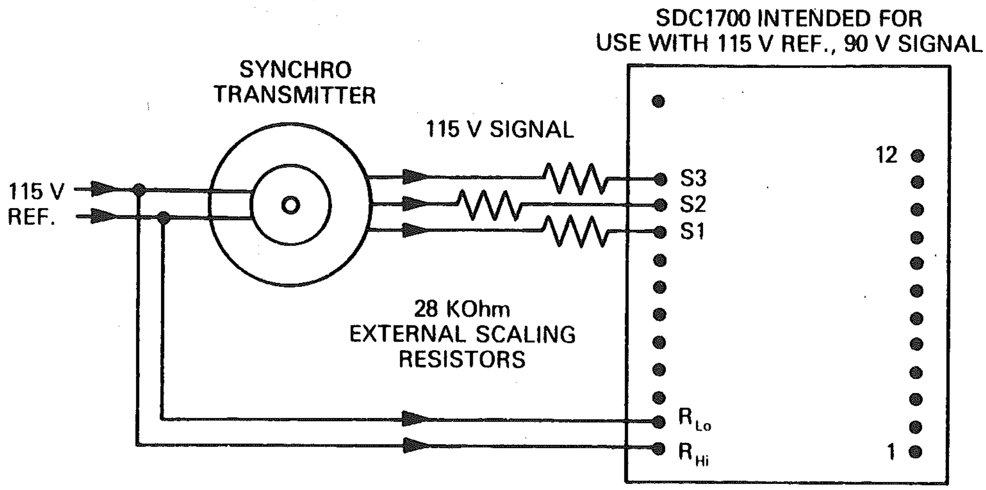


**Fig. 3-28** Resistively scaling the signal input to a synchro to digital converter.

As in the case of the resolver converter example in Fig. 3-27, the matching and temperature characteristics of the resistors is more important than their absolute value. In general a 1% difference between the values will give rise to an extra 17 Arc. Mins. of error while a difference of 0.1% will cause an extra error of 1.7 Arc. Mins. The method of calculating the resistor valves is given in the appropriate data sheets.

In some cases, the reference voltage will need to be scaled also and information on this is given under the 'Reference voltage' heading in this section.

The ability to resistively scale the signal and reference voltages in tracking converters, combined with the fact that the accuracy of most of the converters within certain limits is not highly dependent on reference frequency (see heading 'Reference frequency') means that in certain applications one type of converter can be used with a variety of voltages and frequencies.

*Speed voltages*

When a synchro or resolver undergoes a high rotation rate, the device tends to act as an electric motor and produces speed voltages. These voltages are in quadrature (same voltage but 90° out of phase) to the main signal waveform and steps have to be taken in the design of the tracking converter to ensure that they do not cause any jitter (see heading "Jitter"). A detailed discussion of the effect of speed voltages in tracking converters is given in Appendix D.

*Step response*

If a step input is applied to a tracking converter, a finite time will be required for the internal loop to null and produce the required digital output. The step input response needs to be known when for example an SDC is being driven from a digital to synchro converter where a step input can take place in a matter of microseconds. It is also important to appreciate the step response time when multiplexing a number of synchros or resolvers into one converter. Obviously, in this latter case, the synchros or resolvers can be at varying angles and switching from one to the other will cause a step input to the converter.

The step response when used in the context of tracking converter specifications usually refers to the time to settle to within 1 LSB of the quoted accuracy for a step input of 179 degrees. It is always specified as absolute worst case.

However it is sometimes required to know the settling time for steps of less than 179 degrees and this information is shown in Figs. 3-29, 3-30 and 3-31 for the three standard frequency options of the SDC1700 and SDC1704.

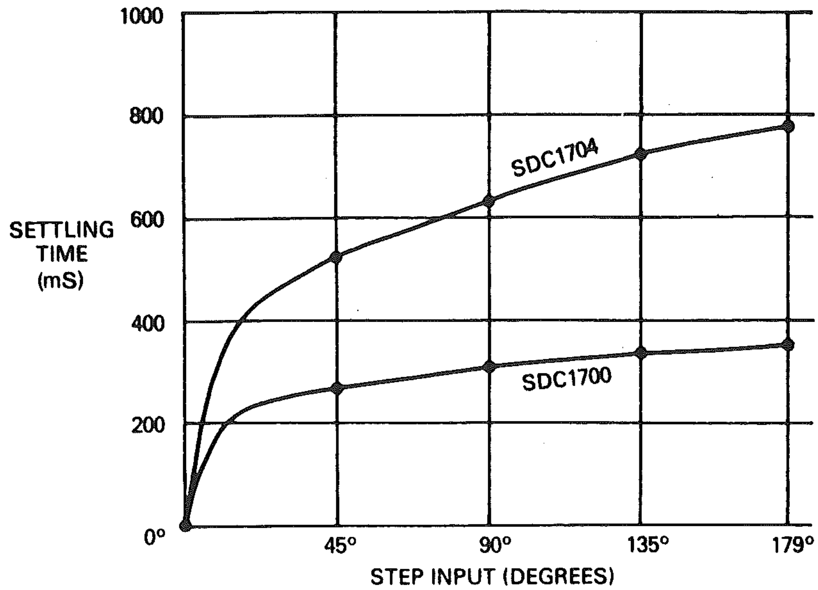


**Fig. 3-29** Typical 60 Hz converter settling times.

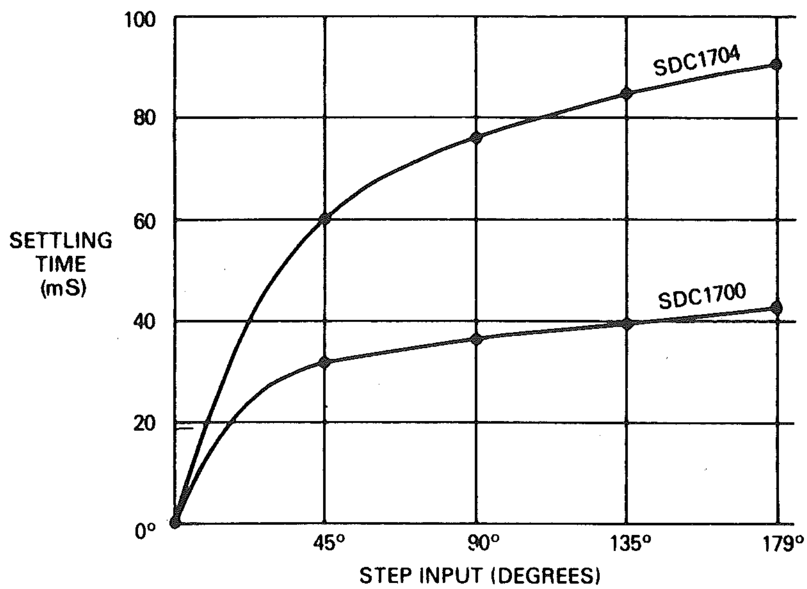


**Fig. 3-30** Typical 400 Hz converter settling times.

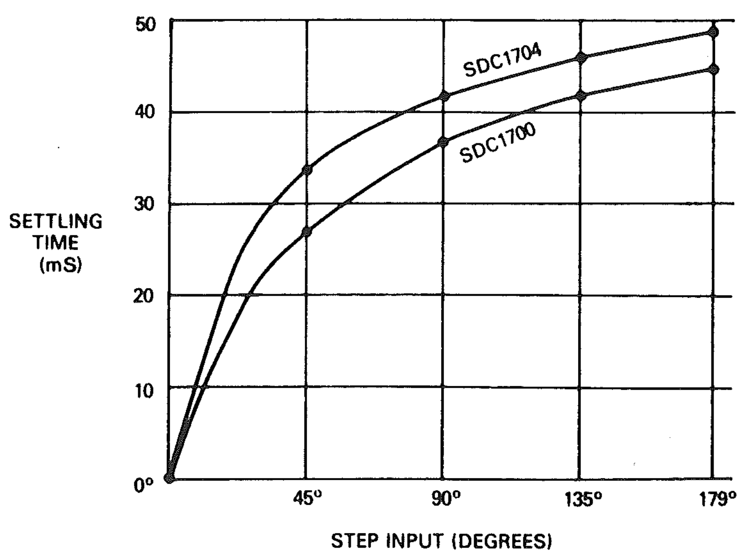


**Fig. 3-31** Typical 2.6 KHz converter settling times.

*Temperature range*
Tracking converters are specified to operate to full accuracy over three different temperature ranges, i.e.

| | |
|---|---|
| 0°C to 70°C | Commercial temperature range |
| −55°C to +105°C | Military temperature range |
| −55°C to +125°C | Military temperature range (Hybrid converters only) |

*Tracking rate*
This is normally specified as the minimum angular speed for which the converter output will be able to keep track of the converter input. The higher the reference frequency for which the converter is intended to operate at, then the higher will be the maximum possible tracking rate.

If the input to the converter rotates at a speed greater than the minimum specified tracking rate, the digital output will become totally unpredictable. Internally, the converter reaches its maximum tracking rate when the input to the V.C.O. (Voltage controlled oscillator) is such that it is outputting pulses to the up-down counter at its maximum possible rate.

The maximum tracking rate of a converter is directly affected by the power supply levels. However although the converters will work at the specified tracking rate over a variation of ±5% in the power supply voltages, the effect on tracking rate and performance in general is unpredictable for variations greater than this.

*Transfer Function*
The transfer function of tracking converters is discussed in the section "Bandwidth and transfer function of tracking converters".

*Velocity voltage output*
Some tracking converters provide a D.C. voltage output which is proportional to the speed of rotation of the input. This is described in this chapter in the section "Velocity Voltage Output".

**Bandwidth and Transfer Function of Tracking Converters**

Traditionally electromechanical servo control loops which have required a digital input command have been based upon control transformers (CT's) driven from digital to synchro converters. See for example chapter IV, Fig. 4-1.

However, it is becoming increasingly common to use a synchro or resolver to digital converter in conjunction with a synchro or resolver transmitter. Such a system is shown in Fig. 3-32.

A system such as that shown in Fig. 3-32 eliminates the need for the power amplifiers

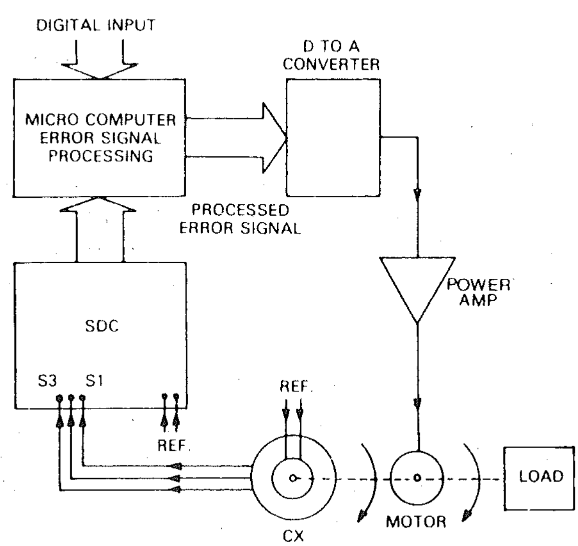


**Fig. 3-32** A synchro to digital converter being used in a digitally controlled servo loop.

required in the digital to synchro converter system in order to drive the control transformer. Since the synchro to digital converter is now in the feedback of the control unit, its transfer function will have to be taken into account in the system design. Clearly the response time of the SDC has to be short compared with the overall system time response. In other words, the frequency response of the converter must be fast compared with the required frequency response of the overall system.

The frequency response of a particular converter can be obtained from the transfer function by the substitution of (jω) for s (where $\omega = 2\pi f$) and taking the modulus of the function.

ie. If the transfer function is of the form:-

$$T(s) = \frac{A(1+Bs)}{Ys^3 + Cs^2 + Xs + A}$$

Then the frequency response corresponding to the particular transfer function is given by:-

$$|T(j\omega)| = \frac{A\sqrt{1+B^2\omega^2}}{\sqrt{(A-C\omega^2)^2 + (X\omega - Y\omega^3)^2}}$$

Plots of the frequency and phase response for the 400 Hz and the 2.6 KHz options of the SDC1700 are given in Figs. 3-33 and 3-34.

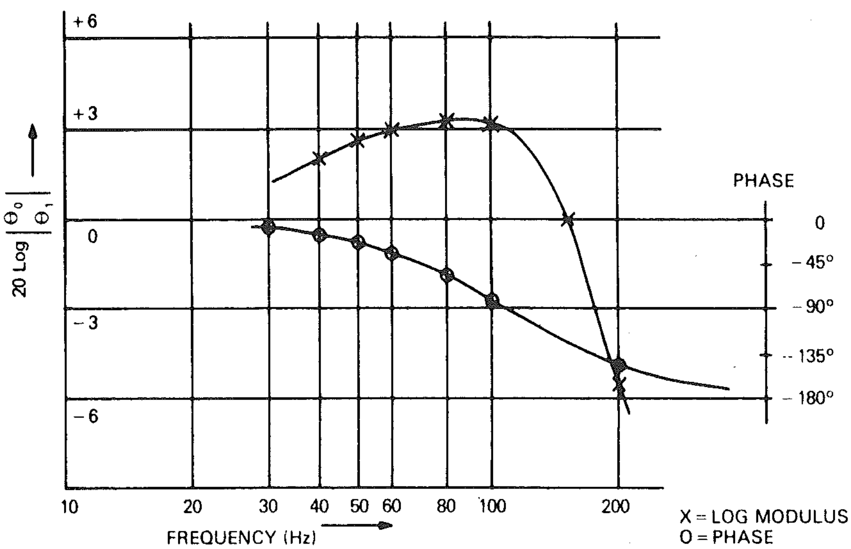


**Fig. 3-33** Frequency and phase response of the SDC1700 400 Hz option.

It should be understood that the transfer functions and frequency responses are for small signal levels only, but in general approximate step changes of 5° will give linear responses while sinusoidal excitation peak inputs of 5° will not cause any amplifier limiting.

When large step inputs are applied, the output will slew at its maximum velocity and a number of overshoots may occur before the response settles down. Step inputs of this type are covered in this chapter in the section "Tracking converter terminology and definitions" under the heading of 'Step response'.

### Synchro to digital coarse/fine (Two speed) systems

Very often it is required to digitise the output of a coarse/fine mechanically geared synchro or resolver system in order to obtain an unambiguous digital word representing the angle of the coarse shaft to an accuracy as good as the gearing imperfections and the backlash referred to the coarse shaft. A similar requirement which is becoming increasingly common is to digitise the output of an electrically geared or multipole resolver. Both of these requirements involve identical techniques and the information contained below should be

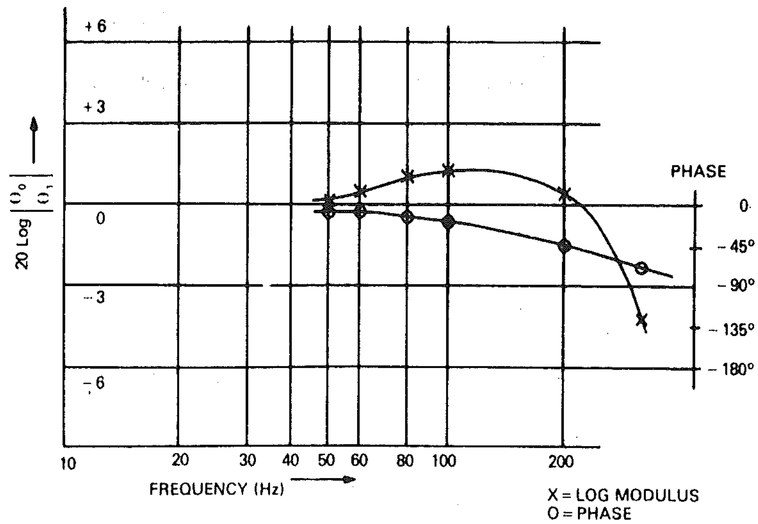


**Fig. 3-34** Frequency and phase response of the SDC1700 2.6 KHz option.

read in conjunction with the electromechanical aspects of coarse/fine systems which are detailed in the "coarse fine systems" section in chapter I.

The problem to be solved in the case of a mechanically geared system is shown in Fig. 3-35 and in the case of an electrically geared or multipole system is shown in Fig. 3-36.

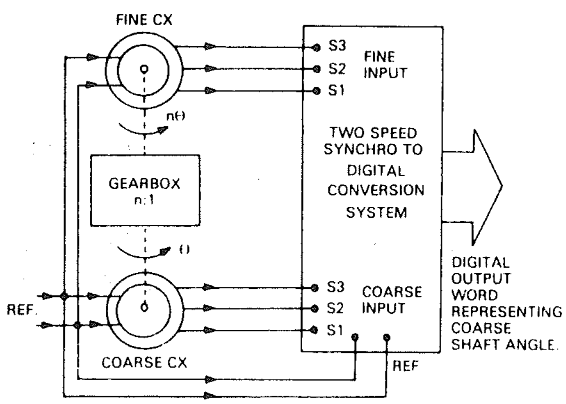


**Fig. 3-35** Two speed synchro to digital conversion with mechanically geared synchros.

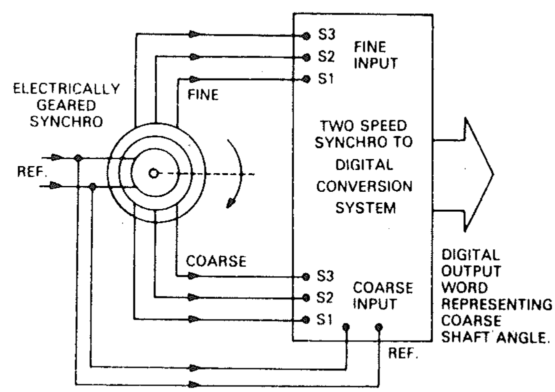


**Fig. 3-36** Two speed resolver to digital conversion with an input from an electrically geared synchro.

*Binary coarse/fine ratios*

For simplicity we shall first assume that the gearing is a binary ratio, say 32:1. Having chosen a binary ratio the fine digital data can be scaled to have the same weight (ie. represent angular change on the coarse shaft) by simply shifting the digits 5 places to the right.

The first step in obtaining the binary output word is to convert both the coarse and fine synchro format angles into digital representations of these angles by the use of synchro to digital converters. The digits representing the fine shaft angle are then shifted five binary places (corresponding to the 32:1 gear ratio chosen for this example) to give them the correct bit weights in terms of the coarse shaft angle. According to the resolution of the synchro to digital converters there will be an overlap of digits from the two sources, and in a theoretically perfect system with no backlash, the overlapping digits will correspond to each other. Let us take an example of a 10 bit SDC on the coarse shaft and a 10 bit SDC on the fine shaft and an angle of 15 degrees. The readings of the two converters allowing for the shift of five binary places in the fine digits are:

| | |
|---|---|
| Coarse digital output | 0000101010 |
| Fine digital output (shifted 5 places) | 0101010101 |
| Combined (15 bit) word representing 15° | 000010101010101 |

See Fig. 3-37.

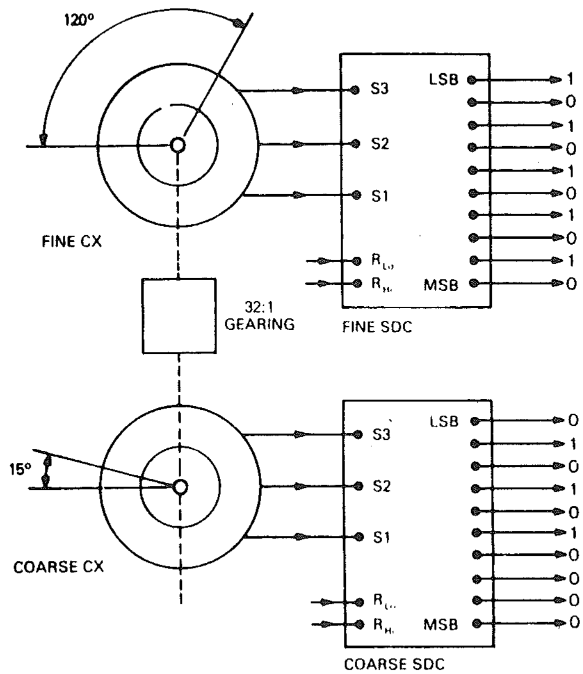


**Fig. 3-37** Two 10 bit SDC's with coarse input angle set at 15°.

In a practical system the overlapping digits will not change together, at the transition points and there will be conflict between the two digital readings. This conflict is resolved by adding extra logic circuits to provide an unambiguous digital output. This logic circuitry is referred to as synchronising logic. The logic circuits use the digits shown as C and D on the coarse reading and the two MSBs marked A and B of the fine digital reading. There are two basic assumptions which should be stated and justified before the logical operation is described, they are:

> The fine digits give the best representation of the coarse shaft angle position.
>
> The backlash etc. which cause the conflicting readings do not represent an angle greater than the digit D on the coarse shaft.
> (This is not a stringent requirement).

The assumption that the angular information given by the fine synchro is the best representation of the coarse shaft position is justified by the facts that if the backlash is represented by $\Delta\phi_1$ on the coarse shaft and the inaccuracy in angle of the coarse synchro and hence the digital information from it is $\Delta\phi_2$, and the inaccuracy of the fine synchro scaled to represent angles on the coarse shaft is $\Delta\phi_3$ then:

$$\Delta\phi_2 > \Delta\phi_1 > \Delta\phi_3$$

This means that we cannot do better than to take the fine digits as being the representation of the coarse shaft angle.

Having said this it is clear that all the digits from the fine converter will appear unchanged at the output. The digits used from the coarse converter may be modified by the synchronising logic circuits.

The logical operations carried out by the synchronising logic circuits are very simple, as shown in the table below:

| | | | |
|---|---|---|---|
| | | ← n → : | CD |
| Coarse digits | → | XXXXX : | XXXXX |
| Shifted fine digits | ↔ | : | XXXXXXXXXX |
| | | | AB |

Gear ratio = $2^n$

| A | B | Operation on digit D |
|---|---|---|
| 0 | 0 | +1 |
| 1 | 1 | −1 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |

(The operation on digit D, either the addition of 1 or the subtraction of 1 carries through to the more significant digits of the coarse converter.)

All it amounts to is either adding or subtracting 1 from digit D or not modifying the digits. The resulting carries or borrowing can affect all the digits to the left of digit D from the coarse converter. The fact that all the digits to the right of D are not modified is of no consequence since they are not used in forming the output word. In this example the output is obtained by using the top 5 bits from the coarse shaft after they have been modified by the synchronising logic and the remaining bits are taken directly from the fine converter output.

The table below shows all the logical states of AB and CD together with the carry or borrow situation that results.

| CD \ AB → | 00 | 01 | 10 | 11 |
|---|---|---|---|---|
| 00 | 0 | 0 | 0 | −1 |
| 01 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 |
| 11 | +1 | 0 | 0 | 0 |

*Non binary ratios*

In the case of non binary ratios between the coarse and fine shaft a similar method is used to resolve the conflicts that can occur, except that in this case it is first necessary to convert the digits to have similar bit weights. For example if the ratio is 36:1 the coarse digital data is multiplied by 36 (by a shift and add multiplier). The synchronising logic is applied to the overlapping digits to produce an unambiguous output angle which is then rescaled back by shift and add multipliers to have the correct bit weights before providing the outputs. Figure 3-38 shows such a system.

*Calculating the resolution of the two speed output for a given ratio*

(a) Determine the next binary number, n, which is greater than the ratio. (ie. n can equal 4, 8, 16, 32, 64 etc.) If the ratio itself is a binary number take the next largest binary number as being n.

(b) Take $\text{Log}_2 n$ and subtract 1 from it.

(c) Add the resultant number (which is the number of bits contributed by the coarse converter to the output) to the resolution of the fine converter being used. This gives the total available word length.

For example;

1) Ratio of 18:1 with a 14 bit converter on the fine channel.

Next largest binary number is 32

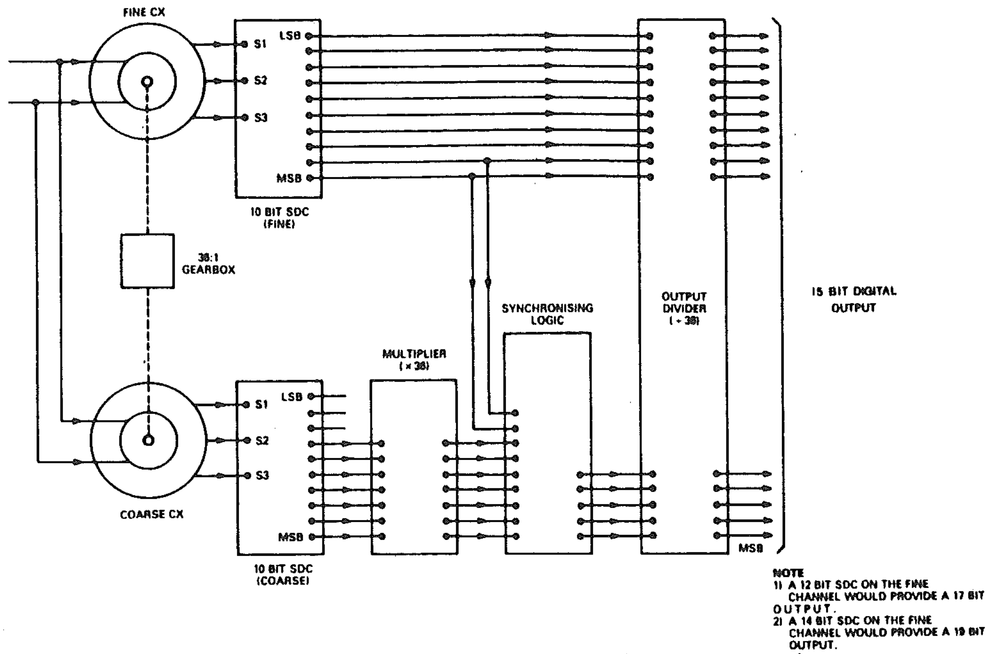


**Fig. 3-38** Two speed logic combination system for non-binary ratios. This example shows a ratio of 36:1.

$\text{Log}_2 32 = 5$
$5 - 1 = 4$

Therefore resolution is $4 + 14 = 18$ bits.

2) Ratio of 16:1 with a 12 bit converter on the fine channel.

Next largest binary number is 32

$\text{Log}_2 32 = 5$
$5 - 1 = 4$

Therefore resolution is $4 + 12 = 16$ bits.

*Accuracy and resolution in coarse/fine synchro and resolver to digital systems*

The examples shown above quite clearly indicate that the resolution of a coarse/fine converter system is dependent on the coarse/fine ratio and the resolution of the fine converter. The higher the ratio and the greater the resolution of the fine converter, the better will be the resolution of the overall system. It is therefore clear that obtaining high resolution is not a problem. For example a 16 bit converter used on the fine shaft of a 64:1 system gives a resolution of:

$$\frac{360}{2^6 + 2^{16}} = 0.31 \text{ Arc. Secs.}$$

(6 bits are contributed by the coarse converter in a 64:1 system.)

Therefore, what is important is the accuracy of the system.

The section on coarse/fine systems in chapter I shows that the accuracy of transmission of a coarse/fine electromechanical system is:

$$B_t + C_t + \frac{S_t}{N}$$

where $B_t$ is the backlash in the gearbox
$C_t$ are the cyclic errors in the gearing with respect to the coarse shaft
$S_t$ is the fine synchro accuracy
N is the coarse/fine ratio

Therefore the accuracy of transmission of a digitised coarse/fine system needs the accuracy of the fine converter added into the equation, eg.

Overall accuracy is given by:

$$B_t + C_t + \frac{(D_t + S_t)}{N}$$

where $D_t$ is the accuracy of the fine converter.

Thus suppose we have a 14 bit converter on the fine channel with an overall accuracy of ±4 Arc. Mins. and the other accuracies in the system are as follows:

$S_t$ = ±6 Arc. Mins.

$B_t$ = ±½ Arc. Min.

$C_t$ = ±¼ Arc. Min.

N = 36:1

The overall accuracy of the system is given by:

$$\tfrac{1}{2} + \tfrac{1}{4} + \frac{10}{36} = 1.02 \text{ Arc. Mins.}$$

*Coarse/fine converter systems*

Various devices are available to perform the synchronising and dividing functions required to combine the outputs of the coarse and fine SDC's or RDC's. Such a device is the TSL1612 Two speed logic processor. This unit is available factory programmed to suit any ratio from 2:1 to 36:1. The TSL1612 is shown connected to 2 SDC's in Fig. 3-39.

If a ratio is required that cannot be met by the TSL1612, a 32×8 P.R.O.M. (Programmable Read Only Memory) can be used to double any ratio. This is shown in Fig. 3-40.

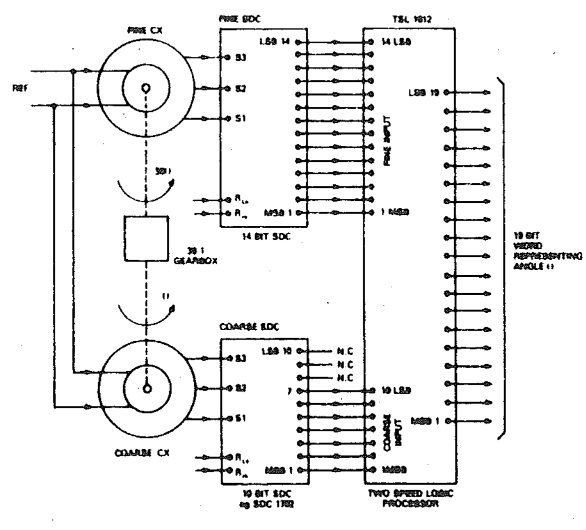


Fig. 3-39 The TSL1612 connected to two SDC's.

## Velocity voltage outputs from tracking converters

*Introduction*

The tracking synchro and resolver to digital converters discussed in this book include some types which in addition to providing a digital representation of the input angle also provide a D.C. voltage proportional to the rate at which the input to the converter is changing. This so called velocity voltage is taken from the input to the V.C.O. inside the converter and is

PROM TRUTH TABLE

| | A4 | A3 | A2 | A1 | A0 | O1 | O2 to O8 |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | X |
| 1 | 0 | 0 | 0 | 0 | 1 | 0 | X |
| 2 | 0 | 0 | 0 | 1 | 0 | 0 | X |
| 3 | 0 | 0 | 0 | 1 | 1 | 0 | X |
| 4 | 0 | 0 | 1 | 0 | 0 | 0 | X |
| 5 | 0 | 0 | 1 | 0 | 1 | 0 | X |
| 6 | 0 | 0 | 1 | 1 | 0 | 0 | X |
| 7 | 0 | 0 | 1 | 1 | 1 | 0 | X |
| 8 | 0 | 1 | 0 | 0 | 0 | 0 | X |
| 9 | 0 | 1 | 0 | 0 | 1 | 0 | X |
| 10 | 0 | 1 | 0 | 1 | 0 | 0 | X |
| 11 | 0 | 1 | 0 | 1 | 1 | 0 | X |
| 12 | 0 | 1 | 1 | 0 | 0 | 1 | X |
| 13 | 0 | 1 | 1 | 0 | 1 | 0 | X |
| 14 | 0 | 1 | 1 | 1 | 0 | 0 | X |
| 15 | 0 | 1 | 1 | 1 | 1 | 0 | X |
| 16 | 1 | 0 | 0 | 0 | 0 | 1 | X |
| 17 | 1 | 0 | 0 | 0 | 1 | 1 | X |
| 18 | 1 | 0 | 0 | 1 | 0 | 1 | X |
| 19 | 1 | 0 | 0 | 1 | 1 | 0 | X |
| 20 | 1 | 0 | 1 | 0 | 0 | 1 | X |
| 21 | 1 | 0 | 1 | 0 | 1 | 1 | X |
| 22 | 1 | 0 | 1 | 1 | 0 | 1 | X |
| 23 | 1 | 0 | 1 | 1 | 1 | 1 | X |
| 24 | 1 | 1 | 0 | 0 | 0 | 1 | X |
| 25 | 1 | 1 | 0 | 0 | 1 | 1 | X |
| 26 | 1 | 1 | 0 | 1 | 0 | 1 | X |
| 27 | 1 | 1 | 0 | 1 | 1 | 1 | X |
| 28 | 1 | 1 | 1 | 0 | 0 | 1 | X |
| 29 | 1 | 1 | 1 | 0 | 1 | 1 | X |
| 30 | 1 | 1 | 1 | 1 | 0 | 1 | X |
| 31 | 1 | 1 | 1 | 1 | 1 | 1 | X |

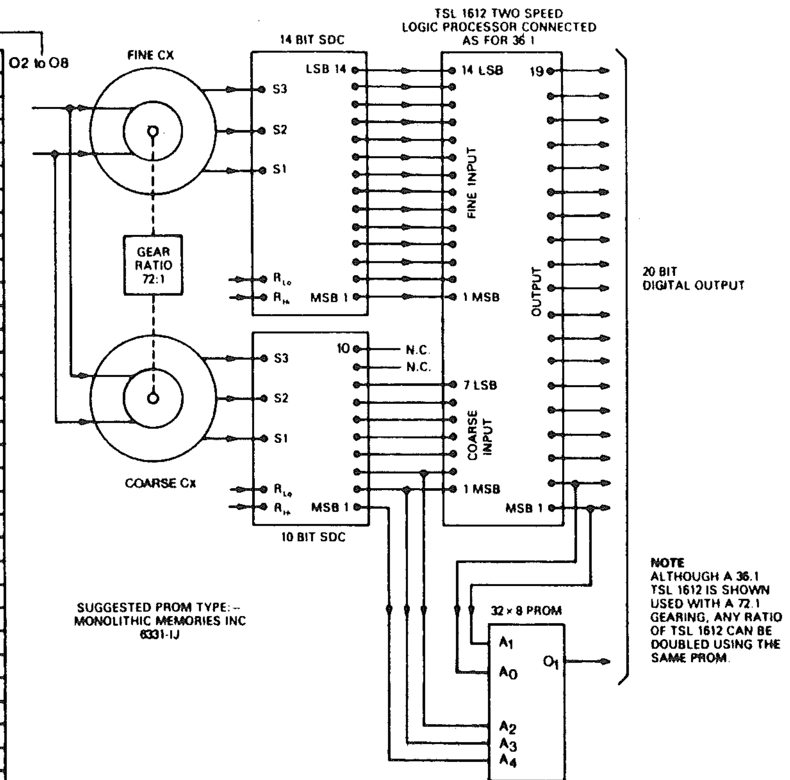


**Fig. 3-40** Doubling a ratio with a P.R.O.M.

normally ± 10 volts nominal output for ± Max. tracking rate of the converter. The velocity voltage output can often be used to replace an electromechanical tachometer in system control loops.

*Velocity Voltages used in Digitally Controlled Feedback Loops*
Fig. 3-41 shows the usual method employed for the control of large servo systems such as those used in gun turrets, missile launchers and tracking radars. In this example an electromechanical tachometer generator is being driven from a step up gearbox in order to provide a voltage proportional to speed for stabilisation purposes.

The system shown in Fig. 3-42 is an alternative method and has the following advantages:

1. No electromechanical tachometer is required.
2. The power dissipation of the SDC is less than that of the DSC.
3. The overall system cost is less.
4. The digital processor can be used to process the error signal.

In Fig. 3-42 the velocity voltage from the SDC is used for stabilising the control loop. Both the digital output and the velocity output are in the feedback paths of the system and therefore it will be necessary for the system design engineer to allow for their transfer functions when designing the control loop.

The transfer functions between the input and the digital output of tracking converters is

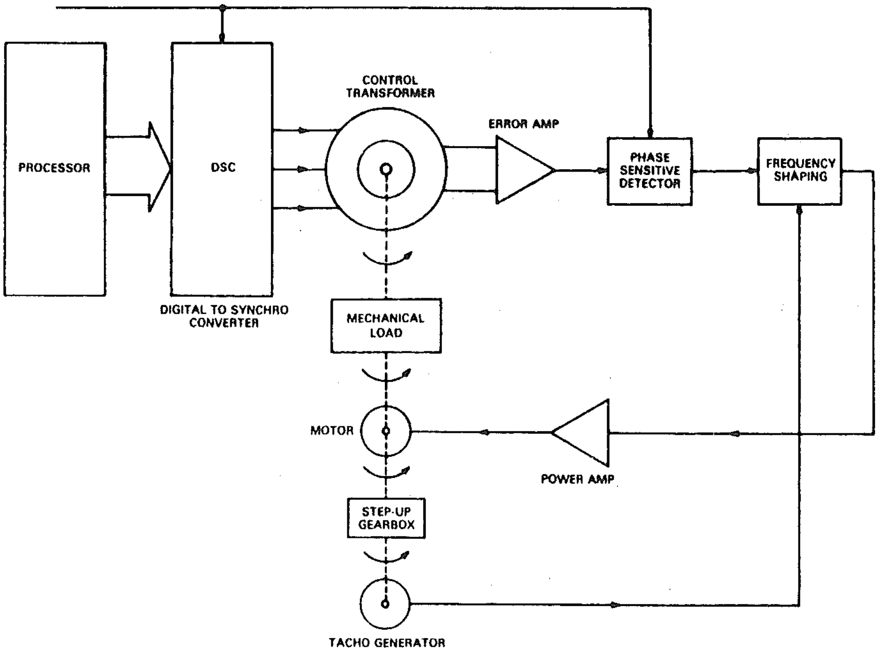


**Fig. 3-41** Usual method of interfacing a computer to a control loop.

discussed in the section "Bandwidth and Transfer function of tracking converters" earlier in this chapter. The transfer function for the input to the velocity voltage output can be obtained from the transfer function by simply adding Ks to the numerator, where K varies for different options but is such as to give 10 volts out for the maximum velocity of the option of converter.

For example, take a converter which has a velocity of 12 revolutions per second for 10 volts velocity output. To find the constant K suppose that the transfer function to the velocity pin is:

$$\frac{\overline{V}}{\overline{\theta}_1} = \frac{Ks \times 121\,(1 + 8.2 \times 10^{-3}s)}{4.8 \times 10^{-6}s^3 + 3.3 \times 10^{-3}s^2 + 0.8s + 121}$$

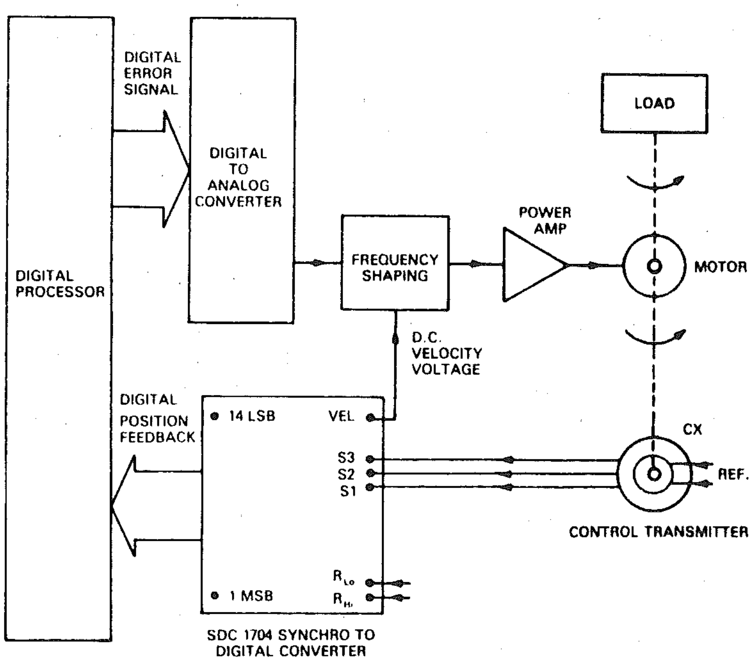


**Fig. 3-42** An SDC being used in a digitally controlled feedback loop.

At a constant velocity of 12 revolutions per second $\overline{\theta}_1$ is given by:

$$\bar{\theta}_1 = \frac{12}{s^2}$$

giving

$$\bar{V} = \frac{Ks \times 121\ (1 + 8.2 \times 10^{-3}s) \times 12}{(4.8 \times 10^{-6}s^3 + 3.3 \times 10^{-3}s^2 + 0.8s + 121)\ s^2}$$

and for large t, the initial transient will have decayed, and since

$$\lim_{s \to 0} sF(s) = \lim_{t \to \infty} f(t)$$

$$V(t) = \frac{K.121 \times 12s^2}{121s^2}$$

and since V(t) = 10 volts for 12 revolutions/sec.

$$K = \frac{10}{12} \text{ volts/revolution}$$

*Velocity feed forward in servo control*

In the control of heavy gun mountings and similar systems, it is not always possible to get type 2 servo control because of the nature of the load and the primary driving source for example when electric Metadyne systems are used. The performance of a type 1 servo loop can be considerably improved and effectively given type 2 loop characteristics by providing "velocity feed forward". This is done by obtaining signals at the input proportional to the input velocity and feeding this voltage in to add to the error signal. Thus at constant velocity the input to the error amplifier in the type 1 loop will be counterbalanced by an equal and opposite voltage causing a zero error signal which is a characteristic of a type 2 loop.

A problem arises when the input signals are in synchro or resolver format since it is not easy to derive a velocity signal directly from them. Hitherto this was overcome by using a small fast acting electromechanical servo control system driven from the input. This electromechanical system was used solely to drive a tachometer which provided the required input velocity voltage.

An alternative solution to this problem is provided by using a fast tracking synchro or resolver to digital converter which gives the required velocity output voltage. The digital output is not used. This solid state solution gives the following advantages:

1. Much lower cost.
2. Totally solid state giving longer life and entirely maintenance free operation.
3. A much better quality signal than can be obtained from an electromechanical tachometer from the point of view of transfer function (less lag) and when suitably filtered from the noise aspect. Note that even when filters are used on the velocity output to suppress high frequency noise, the dynamic performance is still a great improvement over an electromechanical tachometer.

Fig. 3-43 shows the use of an SDC velocity voltage output in a feed forward application.

*Noise on Tracking converter velocity output voltage*

The velocity voltage output of a tracking converter will contain certain ripple voltages due to the residual carrier, ie. the reference waveform. The dominant frequency of the ripple is at twice the carrier and this ripple is deliberately not removed internally since the tolerable amount of smoothing will depend on the particular application. However, it is of course possible to filter the noise externally using a simple RC filter. The photograph in Fig. 3-44 shows the output of the velocity pin of a 400 Hz option SDC1700 for an input rotation of 5

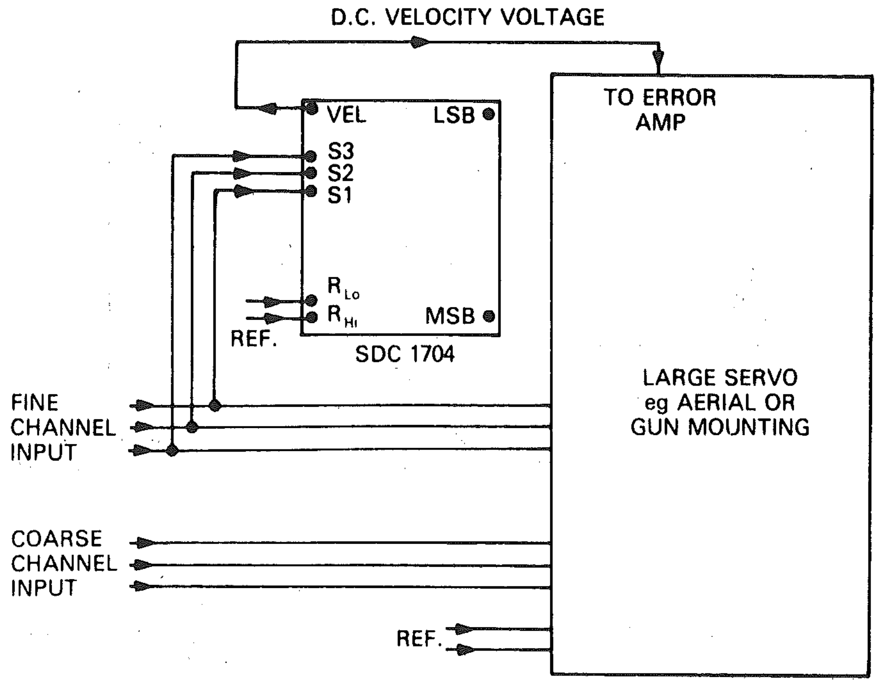


**Fig. 3-43** The use of a velocity voltage output in a velocity feed forward application.

revs per sec. The reference waveform is also shown for comparison purposes. For this photograph, the input to the converter was from a digital to synchro converter and not from an actual synchro transmitter. The ripple voltage could be greater than this with a synchro input because of the associated quadrature speed voltages. See appendix D.

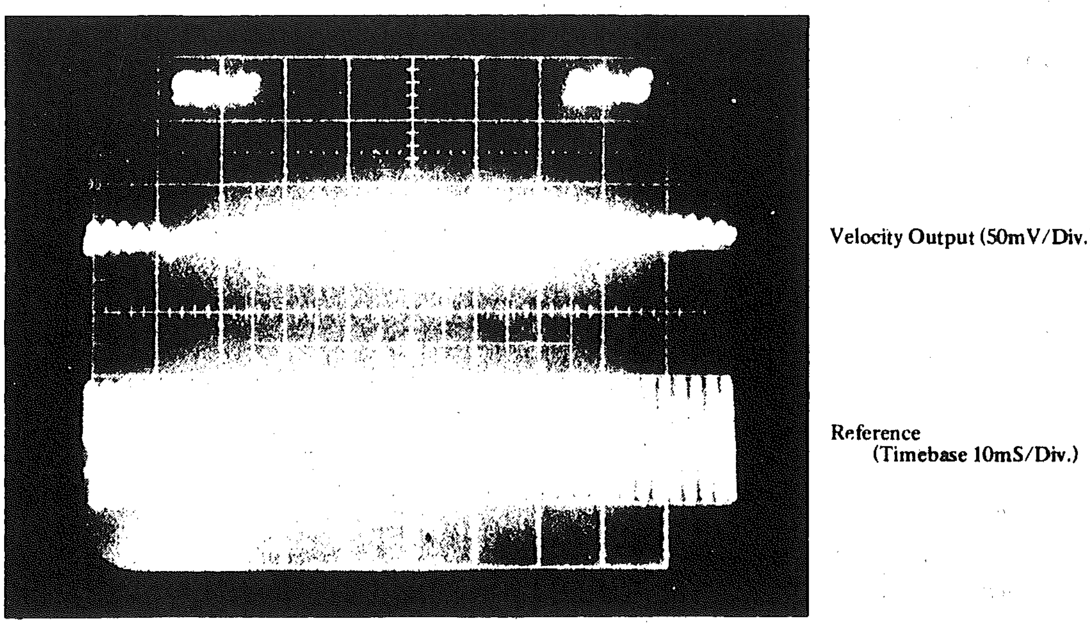


**Fig. 3-44** Velocity output of a 400 Hz SDC1700 at 5 R.P.S.

*Linearity of the velocity voltage of a tracking converter*

The definition of linearity of the velocity output voltage is the worst deviation, in the velocity range specified, from the best straight line which passes through zero velocity at zero voltage. It is expressed as a percentage of the voltage represented by the straight line at the maximum specified velocity. The definition is illustrated in Fig. 3-45.

It is worth noting that in some instances it is advantageous to use a 60 Hz option converter when a velocity output is required in a 400 Hz system. The reason for this is that the lower tracking rate of the 60 Hz converters will provide a higher output voltage per unit rotational velocity. See Figs. 3-20 and 3-23.

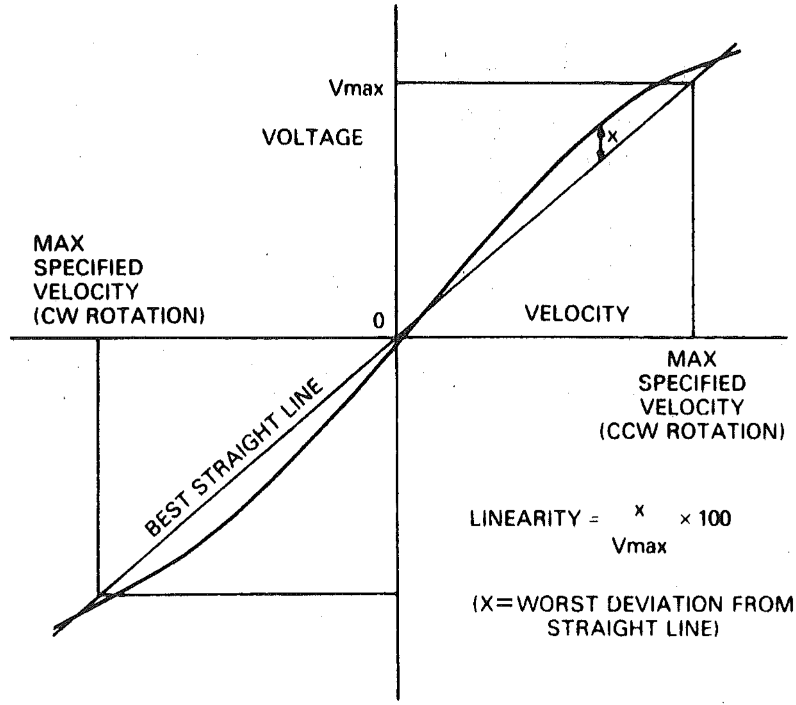


**Fig. 3-45** Method of defining tracking converter velocity output linearity error.

## SUCCESSIVE APPROXIMATION SYNCHRO AND RESOLVER TO DIGITAL CONVERTERS

### Introduction

Fig. 3-46 shows a schematic diagram of a typical successive approximation converter.

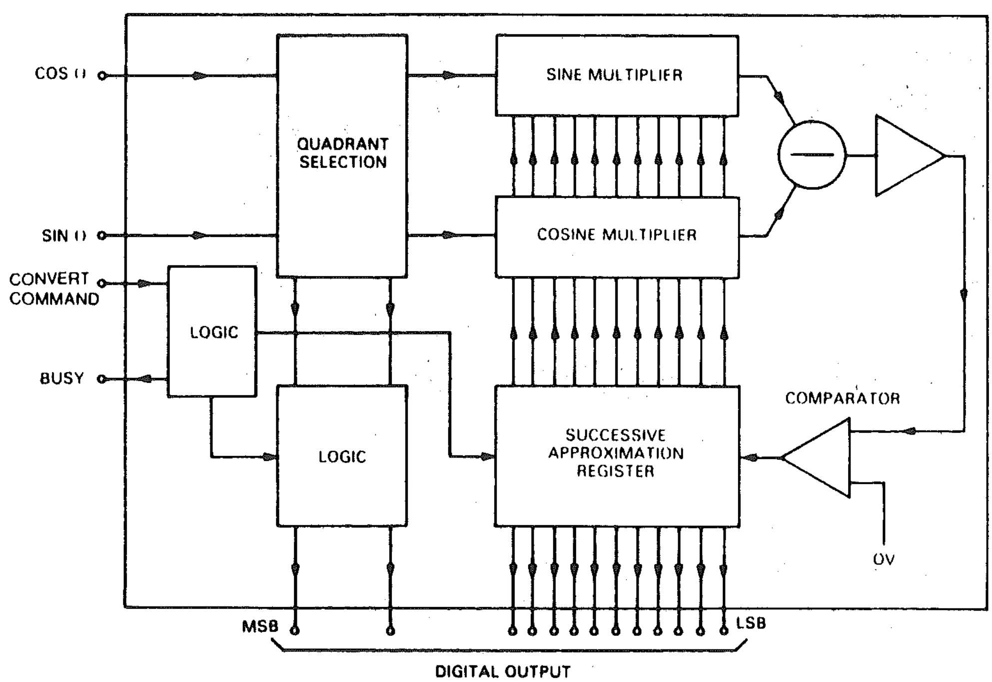


**Fig. 3-46** A successive approximation converter.

In certain aspects the conversion is similar to the tracking type of converter in that a loop is formed using sine and cosine multipliers, but in this case the error signal is nulled by the use of a successive approximation register instead of the V.C.O. and up-down counter. The loop does not act in a continuous tracking mode and requires a convert command signal to initiate each conversion.

The inputs to the converter are two D.C. voltages representing:

$$V \sin \theta$$

$$\text{and} \quad V \cos \theta$$

where θ is the input angle.

Therefore the converter itself cannot accept synchro or resolver format voltages directly but requires the angular information to be in the above D.C. format.

Typical conversion time for this type of converter is between 75 and 150 micro-seconds for 13 bit accuracy.

### Advantages of a successive approximation converter

The main advantage of a successive approximation converter is its cost effectiveness when a large number of channels of synchro or resolver information have to be converted into digital form.

Suppose for example there are 8 channels of slowly changing synchro data to be processed. Clearly, the ideal method would be to use 8 tracking converters from which fresh angular data could be taken at any time from any channel. However, the cost of 8 tracking converters may make this method undesirable, in which case therefore a system of Scott connected transformers, sample and hold amplifiers, a peak detector unit and a successive approximation converter could provide a cost effective solution to this problem. Such a system (showing only 3 of the channels connected) is illustrated in Fig. 3-47.

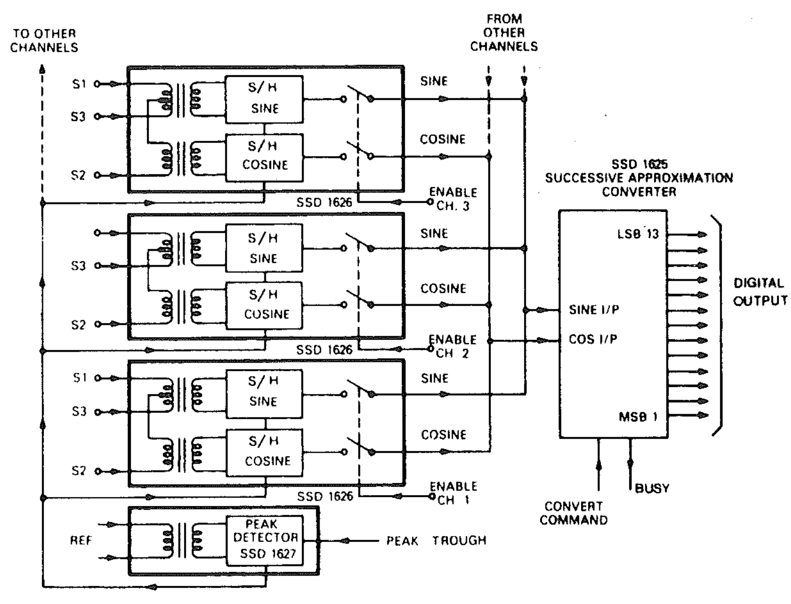


**Fig. 3-47** A successive approximation converter connected to sample and hold amplifiers and a peak detector unit.

In this example, the SSD1626 sample and hold amplifier units which incorporate Scott connected transformers are used in conjunction with the SSD1627 peak detector module to provide D.C. sine and cosine inputs for the SSD1625 converter.

The SSD1627 outputs a SAMPLE signal to each SSD1626 unit on every peak of the reference waveform. On receipt of this SAMPLE signal, each SSD1626 samples and holds the resolver format waveform to provide D.C. voltages which are proportional to the sine and cosine of the input angle. (In an ideal system where no phase shift exists between the reference and signal waveforms, the resolver format signals would be sampled at the peak of their waveforms; however, in practice, the small phase shift which may be present has no effect on the accuracy of the system). An ENABLE on a SSD1626 unit allows the appropriate sine and cosine voltages to be applied to the inputs of the SSD1625. A convert command signal is then applied to the SSD1625 which causes the BUSY to go to a logic 'Hi'. After the conversion time, which is between 75 and 150 microseconds the BUSY returns to a logic 'Lo' state at which time the data on the digital output is valid. The rest of the SSD1626 units can then be enabled and their D.C. voltages converted in the same way.

**Noise on the input signals**

Sampling converters are more sensitive to noise on the input than tracking converters. This is because the input is usually obtained from a single sample of the voltage whereas with the tracking type of converter the frequency shaping circuits effectively average the waveform over many periods of the reference without giving any staleness in the output data for constant velocity inputs.

For applications where the inputs are varying slowly, it is possible to use precision phase sensitive rectification and smoothing instead of sample and hold modules in which case the smoothing will give some immunity to noise.

**Important considerations when connecting the SSD1625, SSD1626 and SSD1627.**

To reduce noise problems when using these components, note should be taken of the following points.

1. To overcome problems due to common ground currents, it is important that a single point in the system is used as a 'Star point' common. Having done this all common (ground) connections from all power supplies and system components should be *taken separately to this 'Star point' and to no other point in the system.*
2. It is important to use separate screened cable for the sine and cosine connections from the sample and hold units to the converter.
3. The screens of the sine cables must not be connected to the screens of the cosine cables. They must also not be connected to any ground or common connection.
4. Each sine cable screen should be connected to the 'Sine Guard' pin on the converter and each cosine cable screen should be connected to the 'Cosine Guard' pin on the converter. The screens should not be connected *to anything else in the system.*