Chapter V

Resolvers and Inductosyns in machine tool and robot control

INTRODUCTION

The applications covered so far have mainly been concerned with military and aerospace requirements. However, resolvers and inductosyns are being used increasingly for machine tool control purposes and this chapter will examine some of the methods of conversion available for this type of application.

INDUCTOSYN TO DIGITAL CONVERSION

Linear Inductosyns

The Farrand Linear Inductosyn has been known for many years as an accurate method of controlling machine tools and other control systems.

The principle of the Linear (and Rotary) Inductosyn is fully described, in Chapter I. An important point to remember about inductosyns is that they are not inherently absolute. i.e. If the power is removed and the slider is shifted by N cycles along the track and the power is restored, the electrical output from the slider will be unchanged. Because of this some systems use additional resolvers geared to the leadscrew in order to provide absolute indication of position.

Inductosyn to digital converters are applicable to all the systems irrespective of whether they are of the geared absolute type or not. In recent designs however the trend has been away from absolute systems, it being sufficient to start from a given datum and keep track of the pitches with an external counter.

Fig. 5-1 shows generally how a tracking Inductosyn/Resolver to digital converter Type IRDC 1730 is connected to the system.

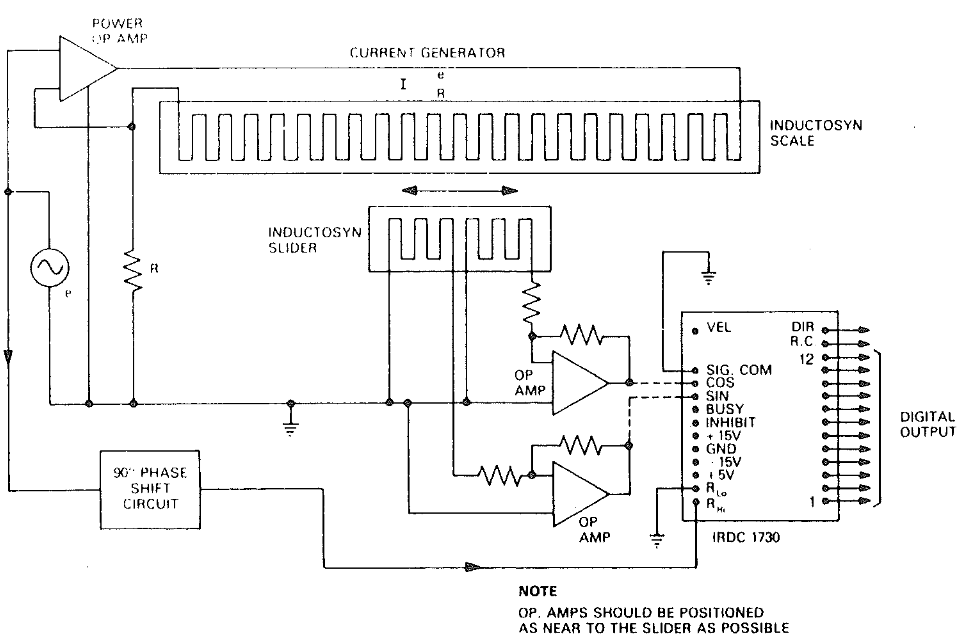

Fig. 5-1 A Tracking Inductosyn/Resolver to digital converter connected to an Inductosyn system.

Tracking Inductosyn to digital converters *can be considered functionally identical to resolver to digital converters*, and in fact tracking converters type IRDC 1730 and IRDC 1731 can be used with both Inductosyns and resolvers. The use of a tracking converter is advisable in the case of Inductosyns as they have the advantages of noise immunity, lack of drift, no external adjustments and no stale data problems.

In the case shown in Fig. 5-1, the Inductosyn is made to behave like a resolver. The fixed track is driven from an AC current generator at a frequency of between 5 and 10 KHz, and the resolver format Sine and Cosine signals are available from the slider. The reason for using a current source is that the track is mainly resisitive and it is better to determine the phase by deliberately driving the track from a current source and inserting a 90 degree phase advance into the reference rather than having a less accurately defined phase shift due to the track's X to R ratio.

The amplifiers which are necessary prior to the converter need to have equal gains in order to amplify the signals to the 2.5 volts r.m.s. required by the converter. (A gain ratio of 1.002 will give rise to an inaccuracy of 1/6000 of a pitch). Suitable amplifiers for this purpose are Analog Devices type AD509 and its output voltage will depend upon the input voltages which in turn depend upon the fixed track current, the frequency, and the spacing between the slider and the fixed track. A typical voltage which might be available at the input to the amplifiers is 20mV. The amplifiers should be connected as close to the slider as possible with the longer connecting leads being at the high voltage level, the low output impedance of the amplifiers will then drive the cable.

Fig. 5-2 shows how the IDC's can be used with a computer in a control loop.

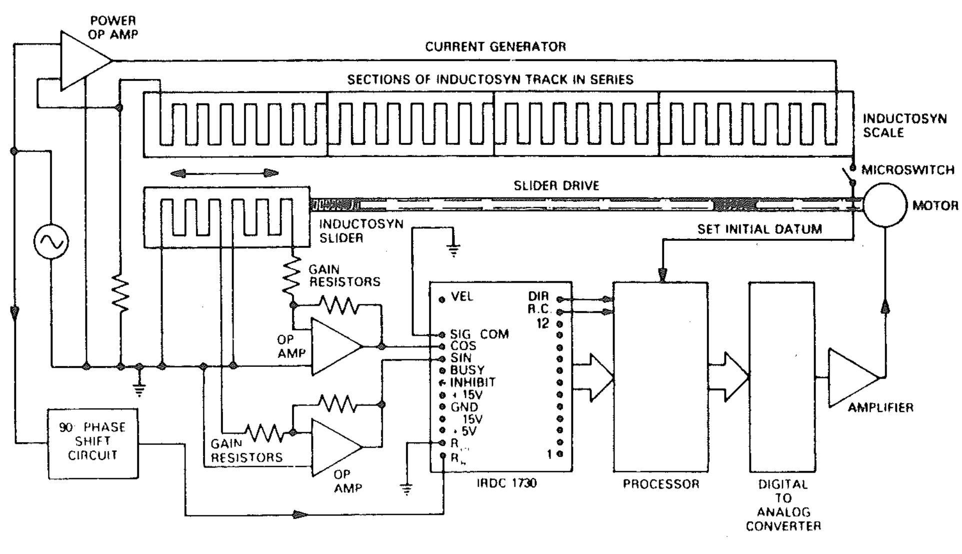

Fig. 5-2 The use of an Inductosyn/Resolver converter in an Inductosyn control loop.

The particular form of interface will depend upon which Inductosyn to digital converter is used. Some converters give parallel data and other converters give serial data with a zero crossing pulse once per complete Inductosyn pitch. For example, the IRDC 1730 gives a 12 bit parallel natural binary output as well as an indication of whether the output is counting up or down. Also given is a pulse (R.C.) which indicates when the converter input has changed from one pitch to the next. The IRDC 1731 gives a serial output of 4000 counts per pitch, as well as a zero crossing pulse which indicates when the slider has moved from one pitch to the adjacent one. The choice of 4000 counts per pitch is sometimes more useful in that it divides the 2mm pitch or 0.1 inch pitch into units which are easily related to the micron and the 0.001 inch. The 4000 counts per period IRDC 1731 also makes the conversion to visual displays very much simpler than the 4096 count IRDC 1730. The 4096 count however may be preferred for computer interfacing.

Concerning the resolution, the 4000 or 4096 counts per period are not justified by accuracy considerations, 10 bits representing 2mm seems to be as high as can be justified by the overall accuracy of the Inductosyn (1 bit corresponds to 0.000077 inches for 10 bit resolution) and it is essentially for smoothness that the 12 bit or 4000 count resolution is required.

Inductosyn converters will generally be required to have very fast tracking and high acceleration performance. The use of carrier frequencies of 5KHz and above makes this requirement attainable.

Concerning the velocity, a linear speed of 10 metres per minute with a 2mm pitch will require a converter capable of tracking at 83 pitches (revolutions) per second. The IDC's should also be at least capable of following accelerations of 1500 pitches/second/second. This acceleration implies that the machine can get up to it's maximum velocity of say 10 metres per minute in a 5mm displacement and similarly can be brought to rest from its maximum velocity. From the point of view of obtaining the maximum velocities, the higher the carrier frequency the better. However the improved performance is of course only obtained when the converter is designed to suit the higher frequency.

The method of transferring data from an IDC is given in the appropriate data sheets, however a method of using external counters with a 4000 count serial output IDC type IRDC 1731 is shown in Fig. 5-3. The number of counters used is dependent on the number of pitches on the Inductosyn.

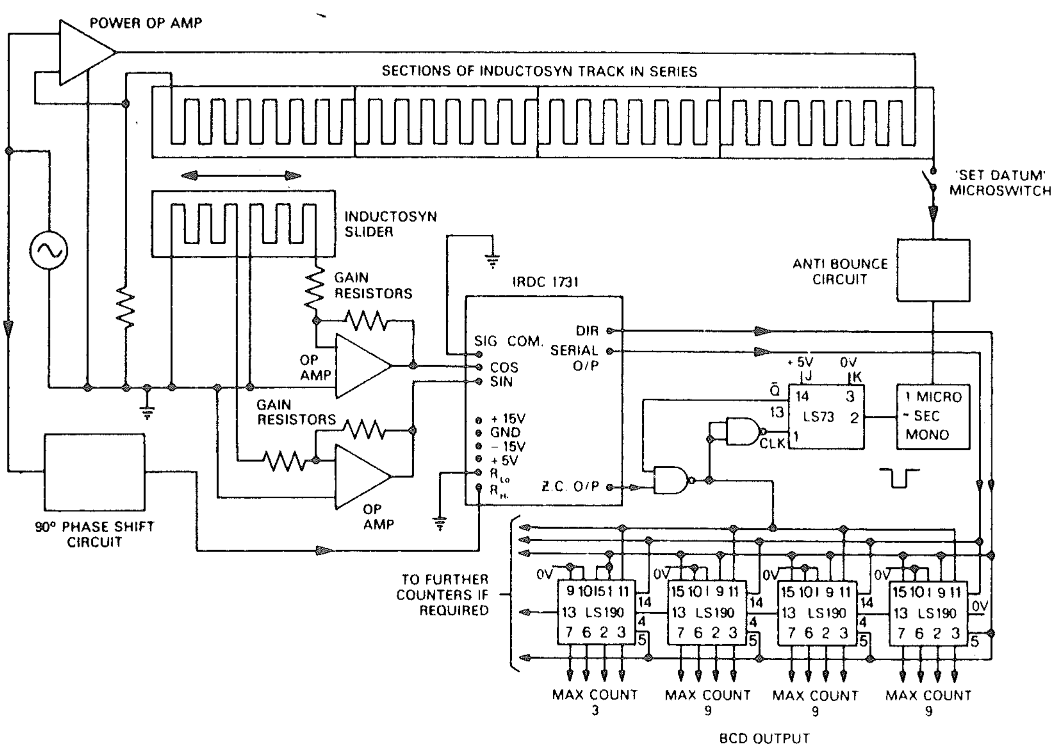

Fig. 5-3 An Inductosyn used with the IRDC 1731 and external counters.

An important point worth considering is concerned with the datum setting. There are two basic types of output from IDC's, i.e. serial and parallel. Since the Inductosyn is basically an incremental method of measurement i.e. the pitches need to be counted, it is necessary to return to the "home pitch" periodically or at switch-on in order to set the pitch counters (e.g. as in Fig. 5-3) to zero. A microswitch or some similar device can be used to determine the "home-pitch". It is important to know that the precision in the positioning of this switch need only be accurate enough to determine the "home pitch". With the serial output type of converter, the first zero crossing pulse on leaving the "home pitch" is then regarded as the datum and is used to start the external counting. In the case of the converters with parallel output, the actual data output within the pitch is accurate and only the pitch counters need to be reset by the microswitch. In neither case does the microswitch determine the zero conditions, the precision zero is given by the data from the converters.

Some of the IDC's (e.g. IRDC 1730) provide a velocity voltage which is suitable for making the control loops in which they are more stable. Concerning this, there is a conflict between the requirement for very high slew rates, and the requirement for a good quality velocity voltage output. Generally, converters which track at high speed give a low output velocity voltage for a given speed and since for a stable system the velocity voltage needs to be noise free for low velocities, the two requirements conflict. The converters have therefore been designed to give the best compromise under these circumstances.

Three Speed Inductosyn Systems

Applications occur in the control of narrow beam radar antennas, radio telescopes, satellite tracking antennas etc., where the very high angular accuracy required involves the use of rotary inductosyns with a high number of poles per revolution. Rotary inductosyns with 360 pitches per revolution are often used for these purposes.

Obtaining an absolute indication of the angle in digital form requires the use of coarse shaft information from an additional synchro or resolver on the coarse shaft. Since the two speed conversion systems which are available are usually limited to 72:1, i.e. a 36:1 system can be doubled (see section on coarse/fine systems in Chapter 3 and in particular Fig. 3-44), it is necessary to include intermediate geared resolvers or synchros to bridge the gap. The gearing used does not need to be of a high precision.

Fig. 5-4 shows the arrangement used to provide a 19 bit digital representation of the angle from a 360 pitch (720 pole) rotary Inductosyn.

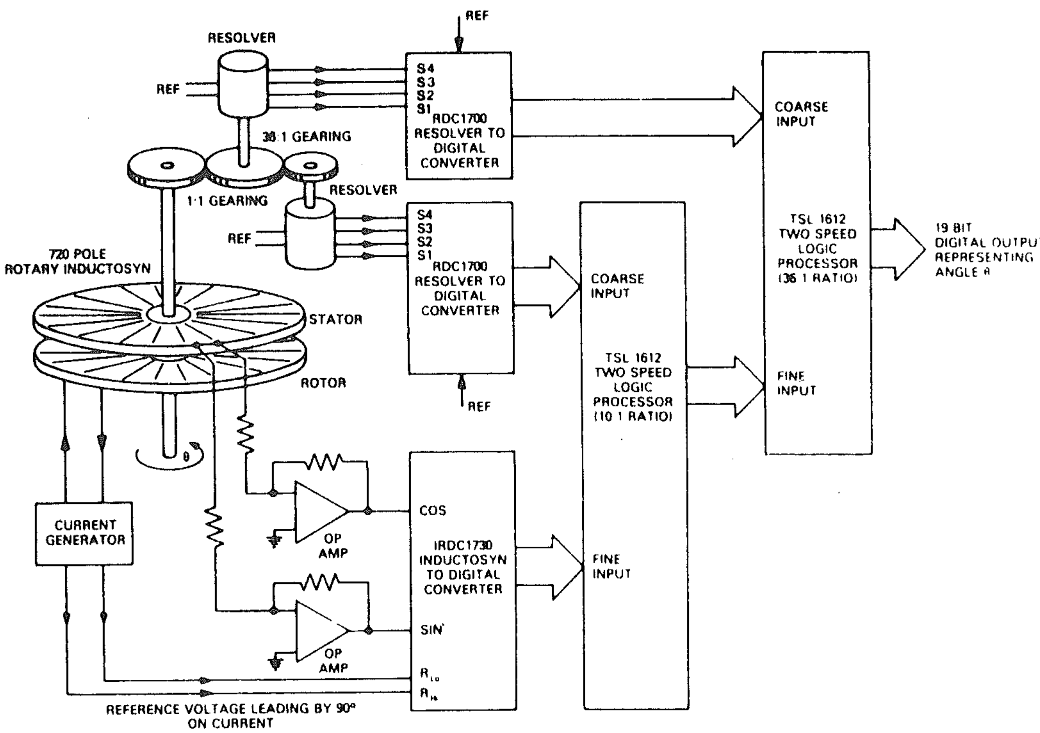

Fig. 5-4 A Three speed system for rotary Inductosyns.

An Alternative Inductosyn Control System Using An RSCT 1621

A simple method of controlling linear motion using the Inductosyn for measurement is shown in Fig. 5-5. The fixed track is driven from a current generator. The phase of the fixed track current is lagged by 90 degrees to compensate for the 90 degree lead in the Inductosyn. (The reference into the phase sensitive detector can be made to lead by 90° instead if this should prove easier). The output voltages from the Inductosyn slider are amplified and provide resolver format inputs into the Resolver Solid State control transformer RSCT 1621. The standard low voltage RSCT 1621 requires 11.8 volts on its input and is transformer coupled.

As the digital inputs are rotated through 360 degrees, the servo loop will move the slider through 1 pitch of the Inductosyn track for each 360 degrees of digital input rotation.

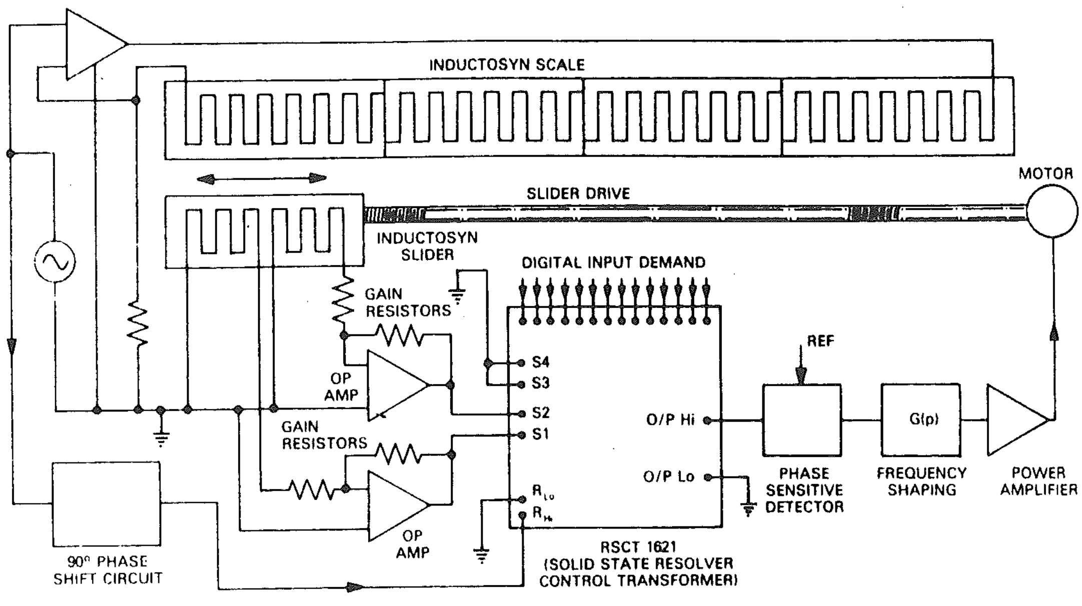

Fig. 5-5 The use of an RSCT 1621 in an Inductosyn control loop.

A disadvantage of this method of control is that there is no velocity voltage available and it will be necessary to obtain feedback from a tachometer or shape the frequency response by other means.

(The standard RSCT 1621 is basically designed for operation at 400Hz and has a 14 bit digital input. If units are required for Inductosyn operation they will need to be additionally tested at the higher frequencies used on the Inductosyn track. The factory should be consulted in this instance.)

THE USE OF RESOLVERS IN LINEAR MEASUREMENT AND CONTROL

In machine tool control the required measurements are often linear displacements. To measure and control these displacements by the use of resolvers, the linear motion must be converted into a rotary motion. There are two principal methods of achieving this, they are by means of a lead screw or by means of a rack and pinion.

There is an important difference between the lead screw and the rack and pinion methods of axis measurement. The leadscrew must be used to transmit the motive force to move the load as well as drive the resolver whereas the rack and pinion method provides an independent and potentially more accurate measurement system. It is worthwhile considering briefly some of the mechanical aspects of both methods.

Rack and Pinion Resolver Drive

A rack and pinion resolver drive is illustrated in Fig. 5-6.

There are several factors which are important in the design of rack and pinion resolver drives. To make the correct choice of pinion size etc., it will be necessary to know the following:-

a) Accuracy expected from the machine.

b) Maximum acceleration.

c) Maximum velocity.

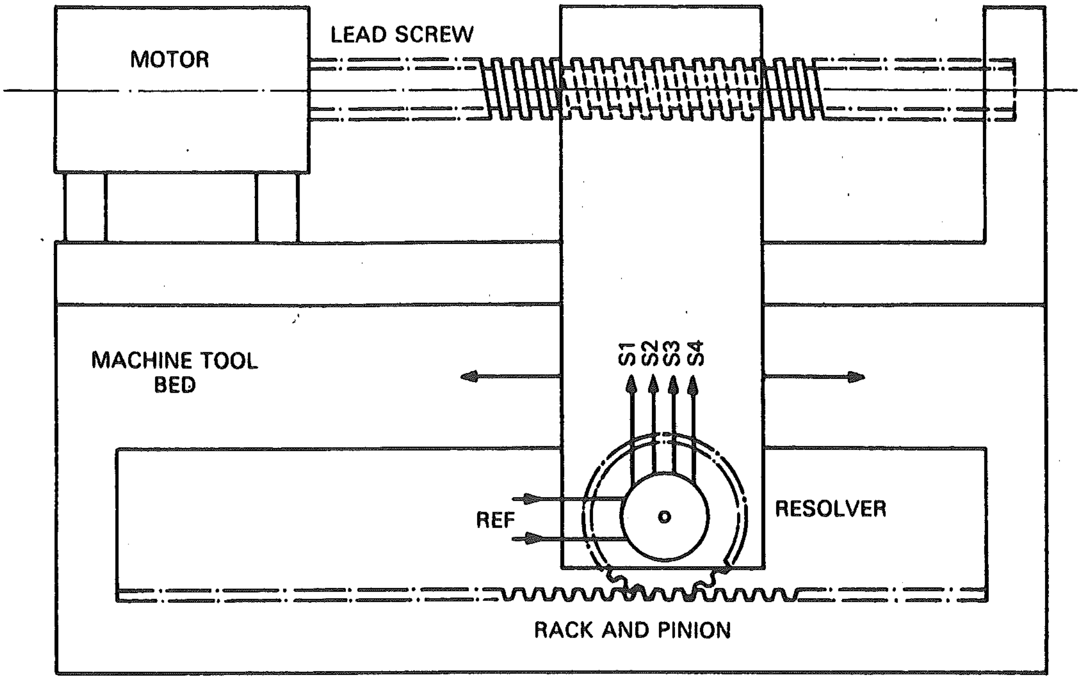

Fig. 5-6 A Rack and Pinion resolver drive.

Static Accuracy

The accuracy attainable from a resolver and resolver to digital converter will typically be 1/4000 part of a revolution. This figure or the equivalent one will determine the maximum diameter of the pinion.

For example, if the effective diameter of the pinion is 5 mm (0.1968 inches) the circumference will be 15.708 mm (0.6184 inches). This means that with an accuracy of the resolver and converter of 1 part in 4000 the overall accuracy will be 0.0039 mm (0.00015 inches). These figures may provide an accuracy which is too high for the requirements in which case a larger diameter pinion wheel may be used.

Torque Considerations

The smaller the diameter of the pinion wheel, the higher will be the angular accelerations for given linear accelerations. The torque produced due to the inertia of the resolver rotor when the machine is accelerating or decelerating is the main cause of wear. For these reasons, if a high accuracy is required together with high acceleration performance, the resolver should be chosen to have a low rotor inertia.

The torques on the pinion are not negligible. For example suppose it is required that the maximum velocity of 10 metres per minute should be reached after a displacement of 10 cm. The linear acceleration is obtained from:-

$$s = \tfrac{1}{2} a t^2$$

$$v = at$$

where
t = time elapsed
s = displacement
a = acceleration
v = final velocity

$$\therefore a = \frac{v^2}{2s} = \left(\frac{10 \times 1000}{60}\right)^2 \times \frac{1}{2 \times 100} = 138.9 \text{ mm/sec}^2$$

This is the circumferential acceleration of the pinion wheel.

For a diameter of 5 mm, the angular acceleration is:

$$\frac{138.9}{5\pi} \text{ revs/Sec}^2$$

$$= 8.8 \text{ revs/Sec}^2$$

The inertia for a size 11 resolver is typically 2.5 gm. mm^2 which gives a torque of:

$$8.8 \times 2\pi \times 250 = 13823 \text{ gm. mm} = 1.3823 \text{ Kg. cm.}$$

The forces caused by these high accelerations should not be disregarded.

Lead Screw Resolver Drive

In the case where the conversion of rotary motion to linear motion is by a lead screw, the lead screw will be powered from a high torque electric or rotary hydraulic motor. For this reason the inertia of the resolver is not important since it can be coupled directly on to the lead screw where its inertia will be negligible. The lead screw method is illustrated in Fig. 5-7.

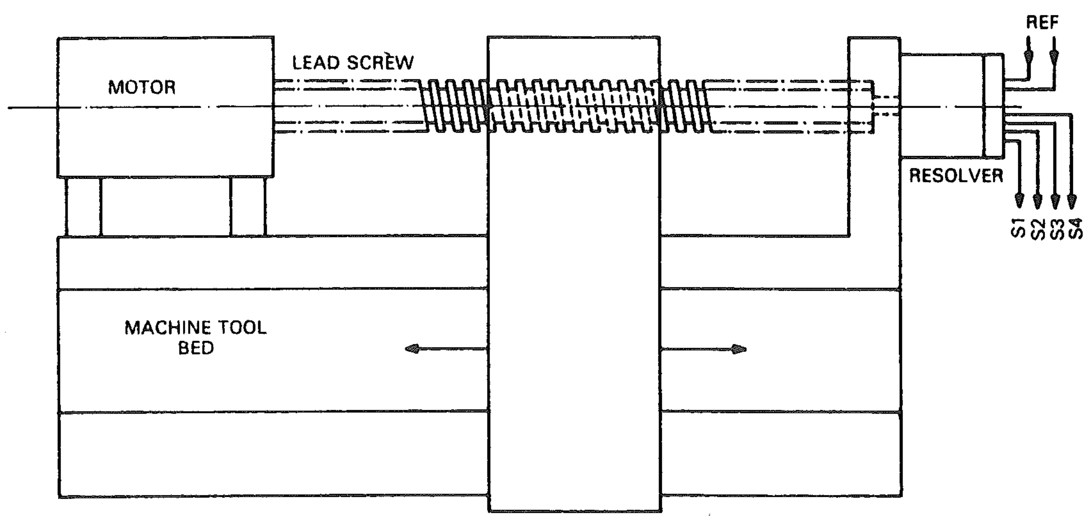

Fig. 5-7 A Lead Screw method of resolver drive.

The pitch on the leadscrew will determine the attainable accuracy. If the resolver is coupled to rotate at the same speed as the lead screw, resolutions in the order of 1/4000 will be attainable electrically. In this case however the measuring is dependent upon the leadscrew accuracy, and any play between it and the load being driven will not be taken out by the feedback loop. For this reason the Inductosyn method is more suitable in some applications.

Resolvers and Converters For Rack and Pinion and Leadscrew Axis Measurement

Resolvers

Brushless resolvers are usually used because of their very high Mean Time Between Failures (MTBF) and their ability to operate successfully under high vibration and shock conditions.

Most brushless resolvers are very tolerant as far as reference frequency and voltage are concerned. A typical brushless resolver will operate from 400 Hz to 10 KHz and the reference voltage can often be between 2 and 40 volts r.m.s.. Because of the wide tolerance on voltage, the resolver manufacturers usually quote the transformation ratio between rotor and stator as opposed to quoting fixed voltages as in the case of Synchros.

One of the factors that can influence the dynamic accuracy of a resolver/converter system is the phase shift between the reference and signal voltages. A phase plot for a typical size 11 brushless resolver is shown in Fig. 5-8.

For this resolver, the best operating frequency would be around 2KHz. There are two reasons for this. Firstly, the phase shift is less at the higher frequency and secondly the effects of the phase shift on the converter are less for the higher frequency reference.

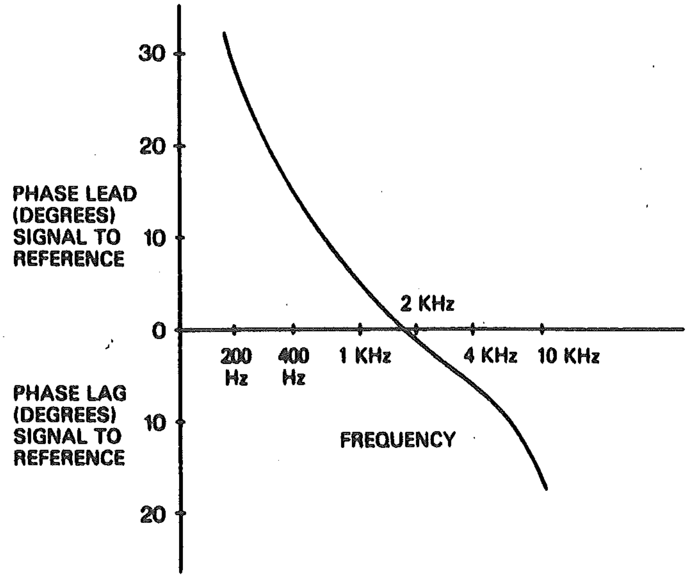

Fig. 5-8 Phase response of a typical size 11 Brushless resolver.

For example, if the resolver shown in Fig. 5-8 is worked at 400 Hz where the phase shift is 16 degrees, at a speed of 20 RPS the velocity error would be:

$$\frac{20}{400} \times 16 = 0.8 \text{ degrees.}$$

If however it was worked at 2KHz the phase would be about 2 degrees giving a velocity error at 20 RPS of:

$$\frac{20}{2000} \times 2 = 0.02 \text{ degrees.}$$

In the case of 400 Hz operation, the phase shift can be corrected by putting an equivalent lead in the reference to the converter in which case the errors would be proportionately less. (See Appendix D on speed voltages).

An alternative method of avoiding errors due to the phase shift is to drive the resolver from a current source. The phase shift will then be a 90 degrees lead. A precise 90 degree lead can then be put in the drive to the phase sensitive detector. The advantage of this method is that it is insensitive to the small phase differences that can be caused by temperature or phase differences between one resolver and another of the same type.

The change of phase shift with temperature is one of the disadvantages of the sometimes used "Phase Analog" method of conversion. With this type of converter the phase changes with temperature have a direct influence on the measurement, i.e. 1 degree phase change due to temperature change will give rise to 1 degree of error. With the tracking method of resolver conversion, the static errors due to phase shifts of up to ± 20 degrees are negligible and the errors at speed are very small providing a suitable reference frequency is selected as described above.

Converters

Tracking converters are ideal for these applications because unlike the multiplexed systems, the data is always fresh and available, ie, there are no stale data problems. The standard resolver to digital converters i.e. RDC 1700, 1702, 1704, 1725, 1726 have a parallel binary output and can be used for machine tool resolver purposes. However, because with both rack and pinion and lead screw methods a number of revolutions of the resolver will be made, it is useful to have an indication of when a full revolution has been made as well as an indication of the direction in which the resolver is rotating. Both of these facilities are provided on the tracking Inductosyn/Resolver to digital converters type IRDC 1730 and IRDC 1731 which can be used very successfully with resolvers as well as Inductosyns.

If the output required is 4000 count serial, then the IRDC 1731 can be used with the resolver as shown in Fig. 5-9. Note that this product was used with the Inductosyn as shown in Fig. 5-3, the only difference here being that scaling resistors may need to be incorporated in order to allow for the higher resolver voltages which have to be fed into the 2.5 volt IRDC 1731 signal inputs.

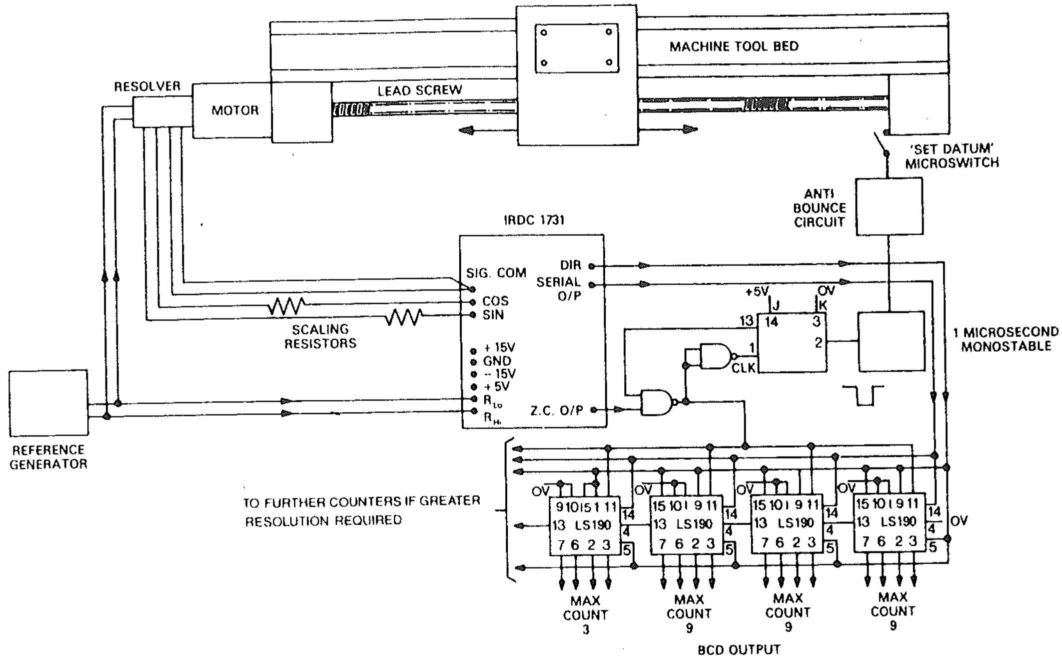

Fig. 5-9 Using the IRDC 1731 with a resolver on a machine tool axis system.

Once again a microswitch can be used as in the case of the Inductosyn system in Fig. 5-3 to indicate when the travel is within the datum point revolution of the resolver. The first zero crossing point after leaving this revolution is regarded as the datum point and initiates the external counting.

If a binary output is required, the IRDC 1730 can be used. Because this gives a 12 bit parallel output as well as a Ripple Clock (zero crossing) output, the datum point can be set electronically. See Fig. 5-10.

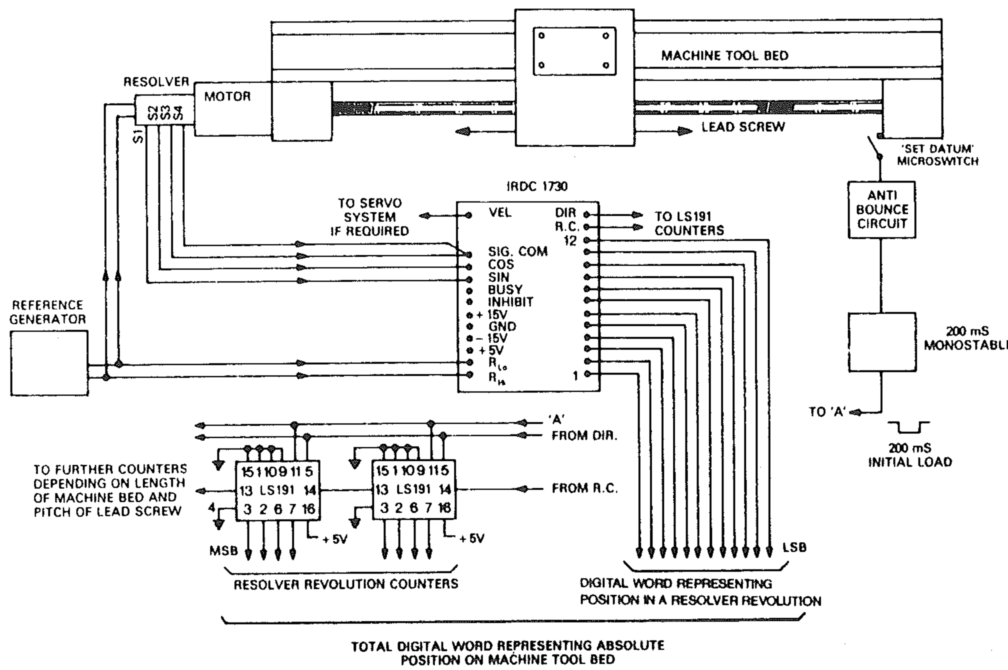

Fig. 5-10 Using the IRDC 1730 with a resolver on a machine tool axis.

As can be seen from the above diagram the external counters register the number of revolutions made by the resolver. The output from the converter is absolute within any revolution and the datum can be chosen arbitrarily within the first revolution. As with the IRDC 1731, the IRDC 1730 is basically suitable for 2½ volt r.m.s. signal and reference inputs and therefore external scaling resistors can be added to cope with higher voltage levels. This is described in the appropriate data sheets.

The Use of a Solid State Resolver Control Transformer in Machine Tool Control

The solid state resolver control transformer provides one of the simplest and lowest cost methods of controlling mechanical movement from digital input data.

A functional diagram of the RSCT 1621 is shown in Fig. 5-11.

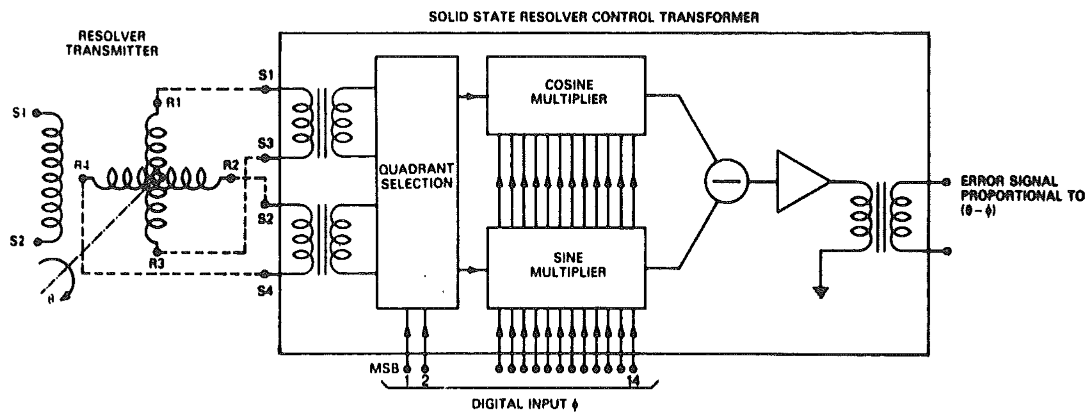

Fig. 5-11 Functional diagram of RSCT 1621 solid state resolver control transformer.

The method of using the RSCT 1621 in a control loop is shown in Fig. 5-12.

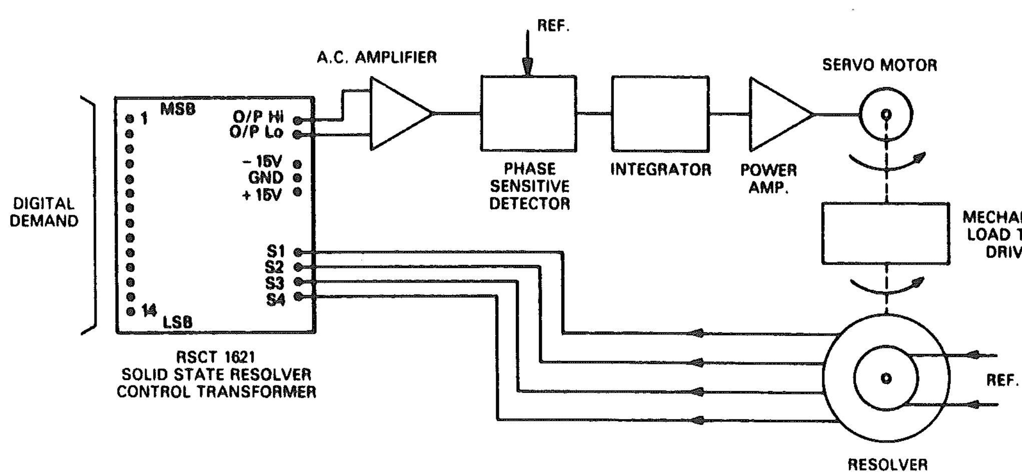

Fig. 5-12 Using the RSCT 1621 in a control loop.

The RSCT 1621 is cost effective because it subtracts the digital demand angle from the angle represented by the resolver feedback signal to produce an AC error signal for the control loop. The error signal can, after amplification be used directly on small biphase motors or as is more usual it can be applied to a phase sensitive detector (as shown in

Fig. 5-12) to provide a DC error signal. Amplification of the AC signal is often carried out before the phase sensitive detector to avoid the effects of any DC offsets in the amplifiers.

Fig. 5-13 shows how the digital input to the RSCT 1621 can be derived from a counter. Serial pulses into the counter can be used to drive the resolver. Pulses at constant rate will give accurate control of the velocity. Alternatively, the computer can be used to give parallel loading of the counter to give step displacements.

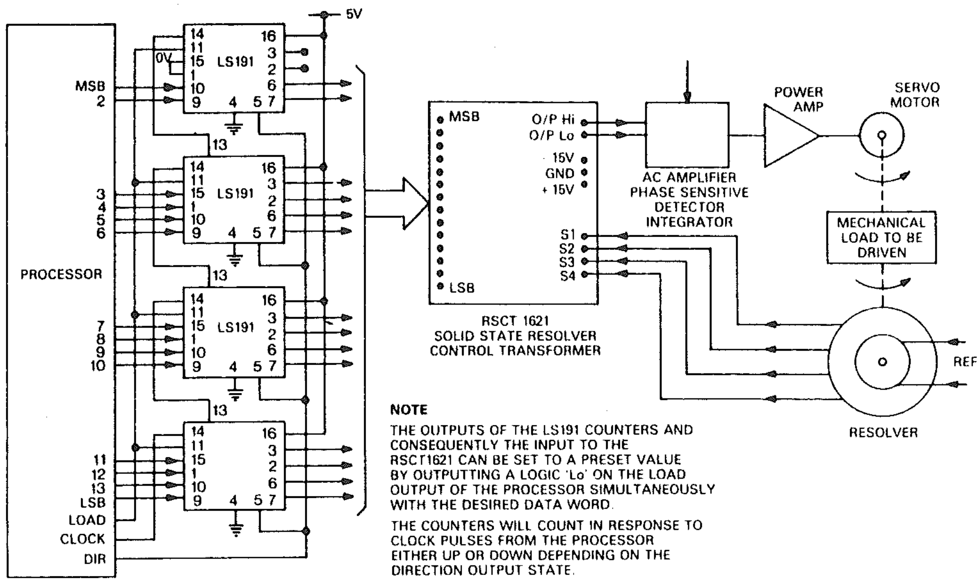

Fig. 5-13 Loading the RSCT 1621 serially using up-down counters.

RESOLVER TO DIGITAL CONVERTERS IN ROBOT CONTROL

A field where resolver to digital converters are finding applications is in automatic Robot control. In the robot some of the movements are driven by hydraulic motors but by its nature, the robot positioning is controlled entirely by the measurement of angles. In the particular type of robot illustrated in Fig. 5-14, nineteen angular movements need to be

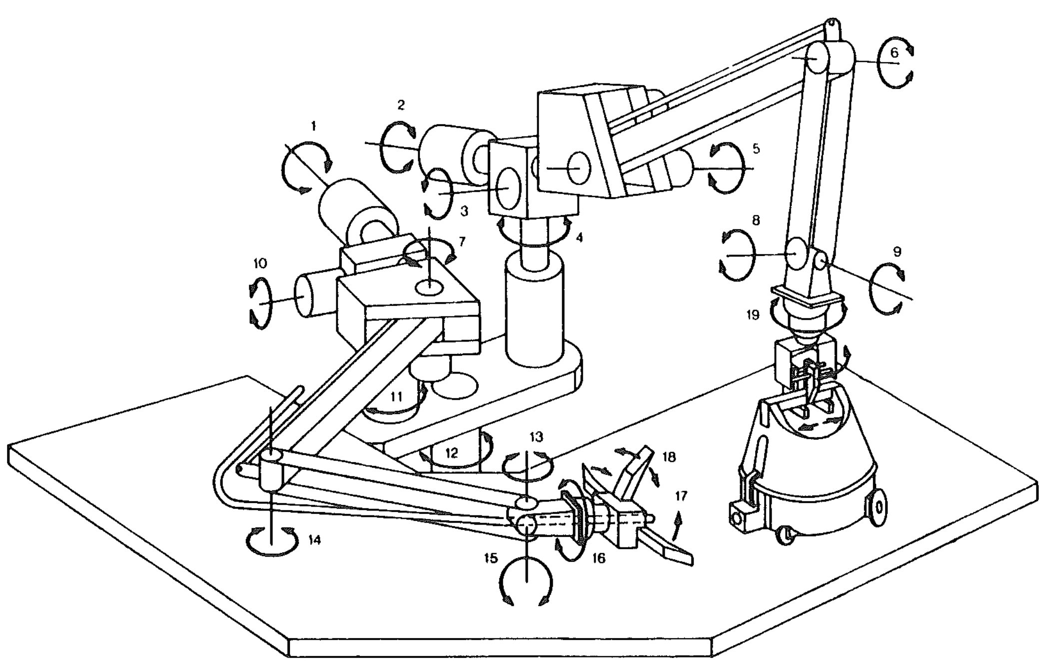

Fig. 5-14 A multi-axis industrial robot.

measured and their data fed back in digital form to the computer. The IRDC 1730 tracking converters are ideal for this application as they can take the information from the resolvers and provide digital angular information together with analog voltages proportional to both velocity and acceleration which can then be used by the servo systems for stabilisation. Particular attention has been taken in the design of the IRDC 1730 to produce a high quality velocity voltage output for this type of application.

Since very high precision is required on some of the axes, geared systems can be used.

For the axes requiring gearing it is necessary to be able to extend the output counter to count the number of revolutions of the resolver. Provision has been made for this on the IRDC 1730 by providing a Ripple Clock (R.C.) ie. revolution counter and a logic level to indicate the direction of rotation of the resolver. The number of revolutions made by the converter can be counted as shown in Fig. 5-10.

CONTROLLING THE VELOCITY OF LINEAR DISPLACEMENTS

In many manufacturing and machine control applications, the required function is to control the linear velocity of a moving part rather than its position. A simple example is in the automatic control of milling machines where the milling cutting tool is often required to traverse at constant velocity across the work piece. Where the linear motion is being produced along a path which is parallel to the machine axis, relatively simple control systems can be used. If the motion is being produced by the addition of two velocities, the design of the control loops will be more critical and it will be important to reduce both static and constant velocity errors.

Type 2 Control Loops

A Type 2 control loop is shown in Fig. 5-15.

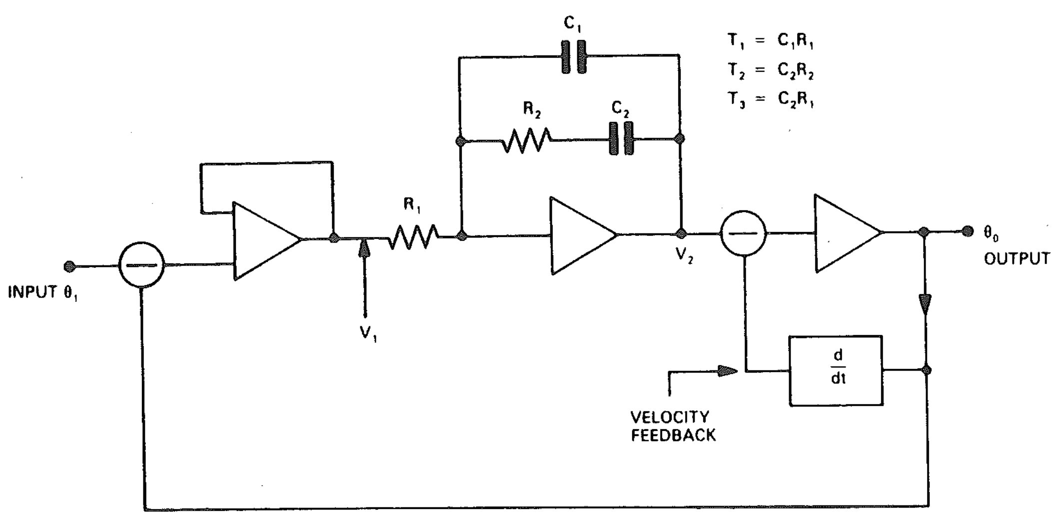

Fig. 5-15 A Type 2 control loop.

This control loop has no errors for displacements or constant velocity and is suitable for applications in which it is important to avoid constant velocity lags.

The transfer function of the control loop of Fig. 5-15 is as below.

$$\frac{\theta_0(s)}{\theta_1(s)} = \frac{K(1 + sT_2)}{s^3T_1T_2 + s^2(T_1 + T_3) + sKT_2 + K}$$

For an input at constant velocity $\theta_1(s) = \frac{V}{s}$

and the error is given by $\varepsilon(t) = \theta_0(t) - \theta_1(t)$

Now writing
$$\frac{\theta_0(s)}{\theta_I(s)} = \frac{A(s)}{B(s)}$$

gives
$$\theta_0(s) - \theta_I(s) = \theta_I(s)\left(\frac{A(s)}{B(s)} - 1\right)$$

To find the error after a long time we use the fact that

$$\lim_{t\to\infty} f(t) = \lim_{s\to 0} s\,F(s) \qquad \text{where } F(s) = L\,f(t)$$

$$\varepsilon(t) = \lim_{s\to 0} L^{-1} s\left(\frac{A(s)}{B(s)} - 1\right)$$

$$= \lim_{s\to 0} L^{-1} s\left(\frac{A(s) - B(s)}{B(s)}\right) = 0$$

$$\text{i.e. } K_v = \infty$$

This demonstrates the fact that there are no constant velocity errors in a type 2 control as shown in Fig. 5-15.

In practice it will not be possible to get the required infinite gains but by using high gains, very good approximations to type 2 control, can be obtained. The velocity feedback from the output makes the transfer function between θ_0 and V_2 equal to $\frac{1}{s}$. i.e. it makes the output amplifiers and motor behave like an integrator. This velocity feedback is an important part of obtaining type 2 control.

Fig. 5-16 shows a practical arrangement in which the velocity signal is derived from the resolver to digital converter in the feedback loop. The required velocity demand is obtained by using the microcomputer to increment one of its internal counters. The microcomputer also carries out digital subtraction to produce the error signal which will be required when the system accelerates.

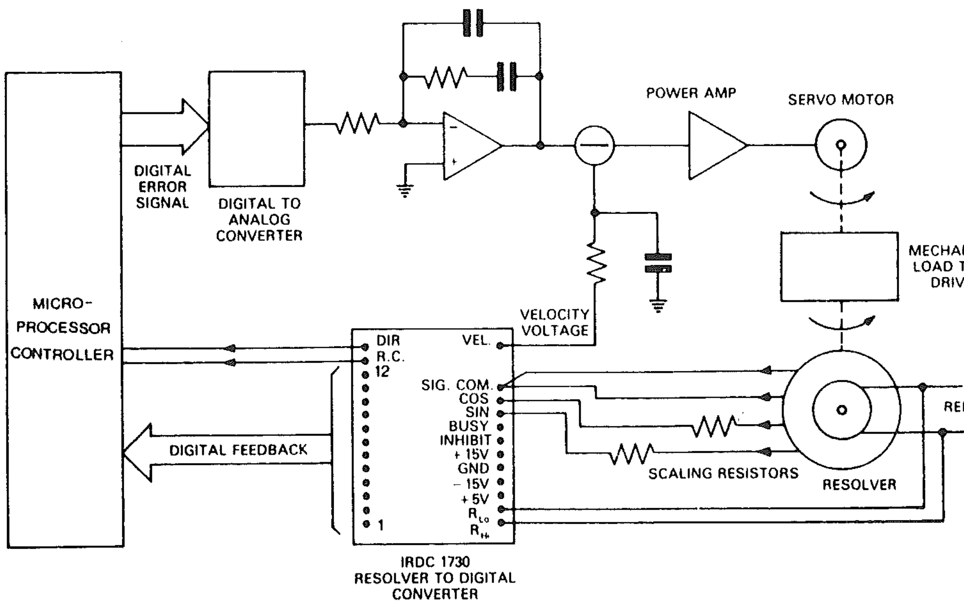

Fig. 5-16 Practical control using the IRDC 1730 as a virtual tachometer.