A Novel Design Method For Resolver To Digital Converter

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ABSTRACT

The importance of reliability make resolvers key building block in flight control and navigation dynamics. The resolvers provide electrical signals related to the sine and cosine of the mechanical shaft angle θ. An analog converter is described for the linearization of these signals and hence for linear computation of θ. The converter was based upon the difference between the absolute values of the transducer signals, together with a single CMOS Type II tracking RDC. This paper gives an overview of the operation principle of a resolver, design methods of Resolver to Digital Converter (RDC). And also proposes a novel design method for an RDC and procedure for selecting the components for the desired RDC bandwidth. The main features of the proposed RDC method are: high accuracy, simple set up, high reliability and stability and good performances. It represents a low cost solution for measuring the angle by means of standard resolvers.

Keywords – **analog control transformer, resolvers, resolver to digital converter, tracking RDC.**

1. INTRODUCTION

Conversion of angular displacement to electrical output requires AC transducers like synchros, resolvers and linear or rotary variable differential transformers. Resolvers are used to transmit angular data electrically from one location to another, where a high degree of accuracy is required. They are also used in many safety critical systems like aircraft, satellite antennas and electromechanical braking systems [1–3]. It has a number of advantages [4–5], such as:

- Operation under severe environmental conditions;
- Capable of high rotational speed and angular acceleration;
- Operation in explosive environments:
- Very high accuracy and immunity to mechanical deformation over a wide temperature range;
- Very high noise immunity when combined with a synchronous demodulator and a ratio metric converter.
- very long distance transmission of the output data before being converted to a digital format in the vicinity of the processor;

Resolvers resemble small motors and have magnetically coupled rotor and stator windings. The analog output of the resolver contains the angular position information that is obtained in digital form using a resolver to digital converter (RDC). Different methods [1–3], [6–11] exist in the literature, focusing on ways to improve the measurement accuracy of the RDC; however, techniques that are cost effective and reasonably accurate are rarely found.

In [6] a method is proposed that measure only the angular position information for a complete 360^0 linear range. However, it does not provide the advantage on saving hardware like oscillators, amplitude demodulators, and consequently weight, size, and cost when compared to the method in [1]. In [1] a software based method is described that is completely implementable digitally in a DSP (or a microcontroller) that provides added flexibility. When both the position and speed estimation is required, Phase Locked Loop (PLL) based tracking loops, are used. In [7] a RDC method is illustrated that uses a bang–bang type phase comparator for fast tracking. However, the method in [7] suffers from tracking errors at high speeds, and out of lock conditions of the PLL, as well as considerable hardware like amplitude demodulators and carrier oscillators.

The problems of accurately estimating the speed and position has been reduced to some extend in [9, 12] at the cost of excessive computations for non-ideal resolvers using off-line methods. The method in [12] represents the resolver or encoder signal as a Fourier series, and the complex coefficients are obtained by evaluating the cross-correlation of the line signals over certain fixed number of periods of the line signals. This demands an evaluation of an integral of the squared error over number of periods of the resolver output signal. As a result of this, this method is not valid for online adaptation for fast point-to-point positioning with small distances using resolver output signals with less than one period [12].

Moreover, with improved manufacturing technology, accurate resolver sensors are often available. There is a need for a novel method that provides fast, computationally efficient, and accurate instantiations estimates of the position as well the speed at reduced hardware and cost using such a resolver angular sensor.

The analog output of the resolver contains the rotor angular position information. Modem systems use the digital approach to extract rotor angle and speed from the resolver output signals. They are called resolver to digital converters (RDCs). Most of RDCs are either trigonometric or angle tracking observers. In the trigonometric approach, the shaft angle is determined by an inverse tangent function of the quotient of the sampled resolver output voltages. This approach can be implemented by different DSP chips, e.g.

Texas Instrument's TMS320F240 [13]. Modem control algorithms for electric drives require knowledge of both the rotor angle and the rotor speed. The trigonometric method, however, only yields values of the unfiltered rotor angle without any speed information. Therefore, for a final application, a speed calculation with smoothing capability should be added. This drawback is eliminated if a special angle-tracking observer (ATO) is utilized. A great advantage of the ATO method, compared to the trigonometric method, is that it smoothly and accurately tracks both the rotor angle and the rotor speed [14].

Resolvers have proven to be quite robust, reliable and of long-life, even while working in very severe and hazardous environment conditions of dust, humidity, temperature, shock, vibration and are almost maintenance free.

2. RESOLVER PRINCIPLE

A resolver sensor consists of two components: a resolver and RDC.

2.1. Resolver

Resolvers are absolute angle transducers, providing two output signals that always allow the detection of the absolute angular position. In addition, they suppress common mode noise. Therefore they are especially useful in a noisy environment. Resolvers used in industry fall into two major categories: housed and frameless, both of which are shown in Fig.1.


Fig.1: (a) Housed Resolver


Fig.1: (b) frameless resolver

Housed resolvers have independent bearings and an output shaft. Frameless resolvers are provided in two pieces, a rotor and stator, which are mounted to the motor. The resolver behaves like a pair of rotating transformers and consisting of one reference winding and two feedback or output windings. The transformation ratio from the reference winding to the two feedback windings varies with the position of the resolver rotor. Resolvers have three windings: a reference, a sine feedback, and a cosine feedback. The reference winding is fixed on the stator and is a sinusoidal signal, typically with a magnitude of 4–8 volts and a frequency of 4kHz–10kHz [15]. The reference winding is magnetically coupled to both stator output windings through the windings located on the rotating shaft. The placement of the reference and output windings with respect to the shaft of a resolver is shown in Fig. 2.

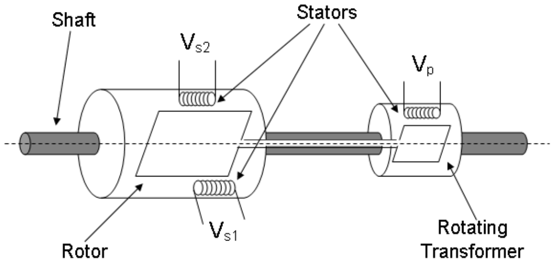

Fig.2: Internal view of a resolver

The two output windings are placed in quadrature on the stator to generate two AC signals 90^0 out of phase [16]. An equivalent cross-sectional view of the resolver with angular position of the rotor, θ with respect to the windings and the associated signals are shown in Fig.3 and Fig.4 respectively.

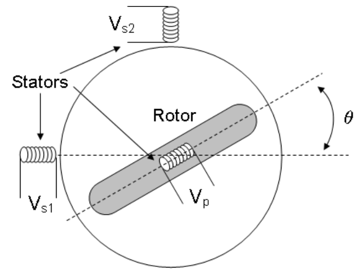

Fig.3: Equivalent cross-sectional view

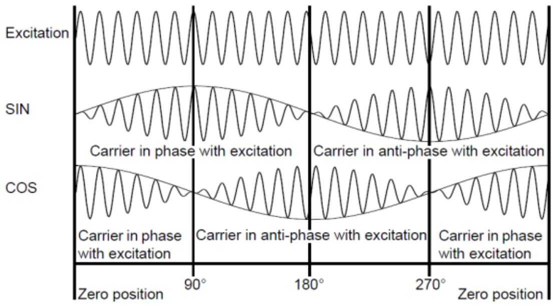

Fig.4: Resolver output signals

In consequence of the excitement applied on the reference winding V_p and along with the angular movement of the motor shaft θ, the respective voltages are generated by resolver output windings V_{s1} and V_{s2}. The frequency of the output voltages is identical to the reference voltage and their amplitudes vary according to the sine and cosine of the shaft angle θ. The winding of the rotor is supplied with a high-frequency sinusoidal carrier signal:

$$V_p = A \cdot Sin(w_c t) \qquad (1)$$

where A is the peak amplitude and $w_c = 2\pi f_c$, where f_c is the frequency (typically V and kHz). The resolver operates as a rotary transformer with two outputs. Assuming that the angular velocity $\frac{d\theta}{dt}$ of the rotor is much lower than w_c, the two stator windings of the resolver modulated signals are given by

$$\left.\begin{aligned} V_{s1} &= \alpha A Sin(\theta) Sin(w_c t) \\ V_{s2} &= \alpha A Cos(\theta) Sin(w_c t) \end{aligned}\right\} \quad (2)$$

where θ is the angular position of the shaft of the resolver and α is the transformation ratio constant between rotor and stator windings. These two output signals V_{s1} and V_{s2} are called as quadrature signals. As the excitation or the carrier signal V_p is an ac signal, the output voltages from the two-stator windings are amplitude modulated, as shown in Fig.4.

2.2. Resolver-to-Digital Converter (RDC)

Formerly resolvers were used primarily in analog design in conjunction with a Resolver Transmitter – Resolver Control Transformer [17]. These systems were frequently employed in servomechanisms, e.g. in aircraft on board instrument systems. However modem systems use the digital approach to extract rotor angle and speed from the resolver output signals. So, the method for obtaining and digitizing the angular position of a resolver is also known as RDC. The block schematic of RDC is shown in Fig.5.

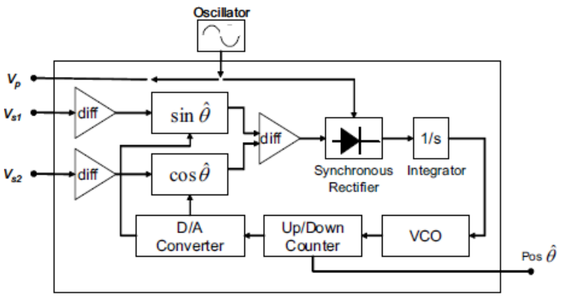

Fig.5: Block schematic of RDC

Most of RDCs are either trigonometric or angle tracking observers.

2.2.1. Trigonometric method

The shaft angle can be determined by an Inverse Tangent function of the quotient of the sampled resolver output voltages V_{s1} and V_{s2}, as shown in Fig.6. This determination can be expressed, in terms of resolver output voltages, as follows:

$$\theta = Tan^{-1}\left[\frac{V_{s1}}{V_{s2}}\right] \quad (3)$$

Calculus of inverse tangent could be done by using Coordinate Rotation Digital Computer (CORDIC) algorithm [18].

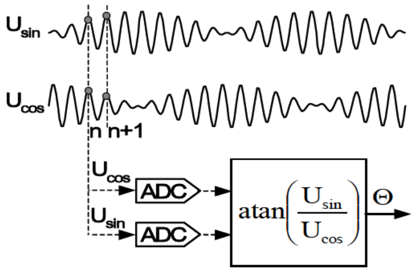

Fig.6: Principle of Trigonometric method

2.2.2. Angle tracking observer (ATO) method

The block schematic of ATO is shown in Fig.7. ATO consists in a closed-loop where it compares values of the resolver output signals V_{SIN}, V_{COS} with their corresponding estimations $\hat{V}_{SIN}, \hat{V}_{COS}$. As in any common closed-loop systems, the intent is to minimize observer error. The observer error is given by subtraction of the estimated resolver rotor angle $\hat{\theta}$ from the actual rotor angle θ. The observer error $\sin(\theta-\hat{\theta})$ is given by:

$$\sin(\theta-\hat{\theta}) = \sin\theta\cos\hat{\theta} - \cos\theta\sin\hat{\theta} \quad (4)$$

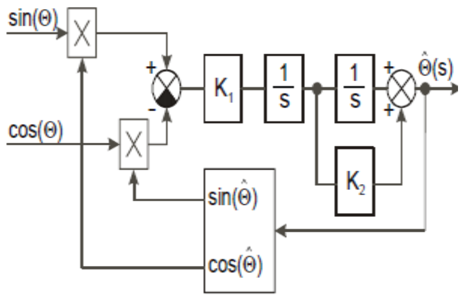

Fig.7: Block schematic of ATO

In case of small deviations of the estimated rotor angle compared to the actual rotor angle, the observer error may be considered in the form $\theta-\hat{\theta}$. A simplified wiring diagram of resolver with RDC is shown in Fig.8.

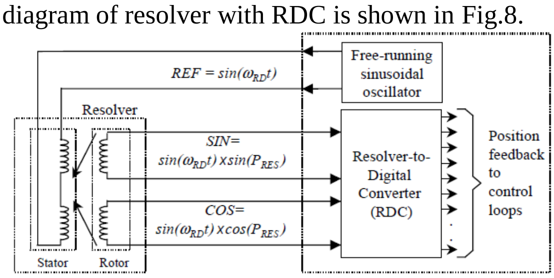

Fig.8: Resolver and RDC wiring

In this paper, a novel design method using CMOS Type II tracking RDC is proposed. The proposed design method is summarized and the procedure to selecting RDC bandwidth is presented in section 3. Results are presented in section 4 and section 5 concludes this paper.

3. PROPOSED DESIGN METHOD

The proposed RDC is a single CMOS Type II tracking RDC. It is implemented using precision analog circuitry and digital logic. For flexibility, the converter bandwidth, dynamics and velocity scaling are externally set with passive components. The block diagram of the proposed RDC is shown in Fig.9. The converter is powered from +5V DC. Analog signals are referenced to signal ground, which is nominally $\frac{V_{CC}}{2}$. Fig.10 shows the transfer function diagram of the proposed method. The converter consists of three main sections: the Analog Control Transformer (CT), the Analog Error Processor (EP) and the Digital Logic Interface. The CT has two analog resolver inputs (Sin and Cos) that are buffered by high impedance input instrumentation amplifiers and the 16 bit digital word which represents the output digital angle.

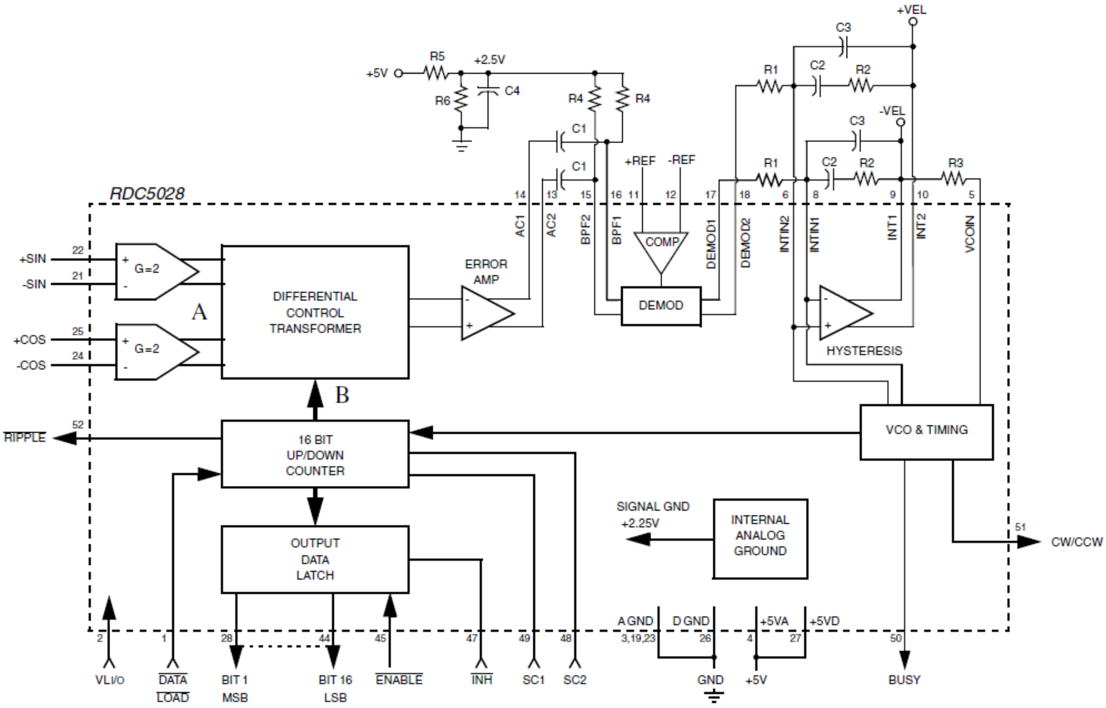

Fig.9: Block diagram of the proposed RDC

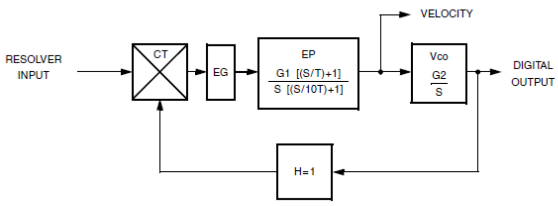

Fig.10: Transfer function diagram

The CT performs the ratio metric trigonometric computation of:

$$Sin(A)Sin(wt)Cos(B) - Cos(A)Sin(wt)Sin(B) = Sin(A-B)Sin(wt) \quad (5)$$

"A" represents the resolver angle; "B" represents the digital angle and $Sin(wt)$ represents the resolver reference carrier frequency. The Error Processor is configured as a critically damped Type II loop. The AC error, $Sin(A-B)Sin(wt)$ is full wave demodulated using the reference squared off as its drive. This DC error is integrated in an analog integrator yielding a velocity voltage which in turn drives a Voltage Controlled Oscillator (VCO). Hysteresis is added to prevent dithering and disables counting when the error is less than 1 LSB. This VCO is an incremental integrator which, together with the velocity integrator, forms a Type II loop. A lead is inserted to stabilize the loop and a lag is inserted at a higher frequency to attenuate the carrier frequency ripple. The error processor drives the 16 bit digital output until it nulls out. Then angle $A = B$. The digital output equals angle input to the accuracy of the precision control transformer. The digital logic interface has a separate power line, VLI/O that sets the interface logic 1 level. It can be set anywhere from +3V to the +5V power supply. The functional block diagram of this method is shown in Fig.11.

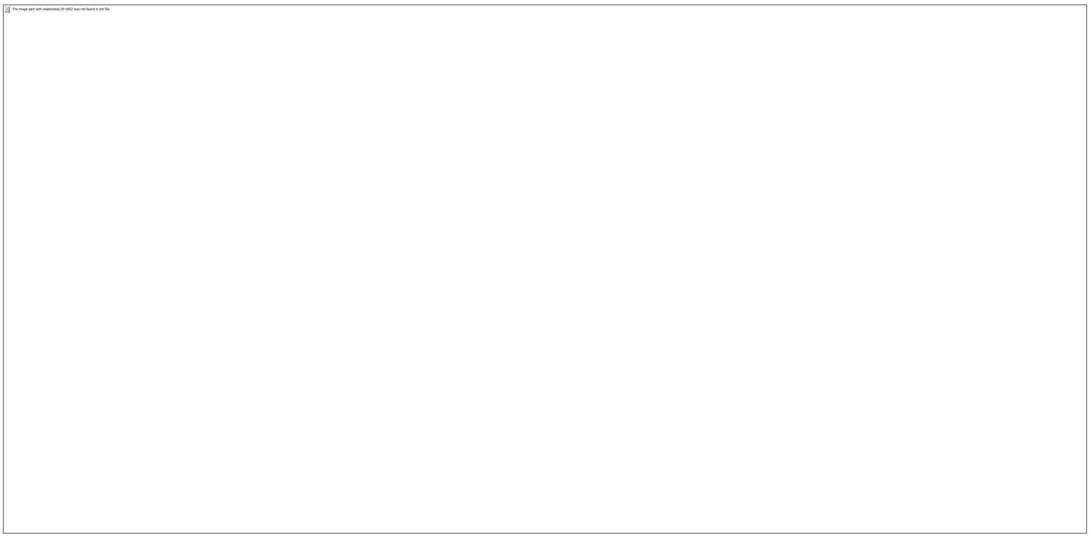

Fig.11: Functional Block diagram

3.1. Transfer Function and Bode Plot

The dynamic performance of the converter is determined from its functional block diagram and Bode plot. The Bode plot of the proposed RDC method is shown Fig.12.

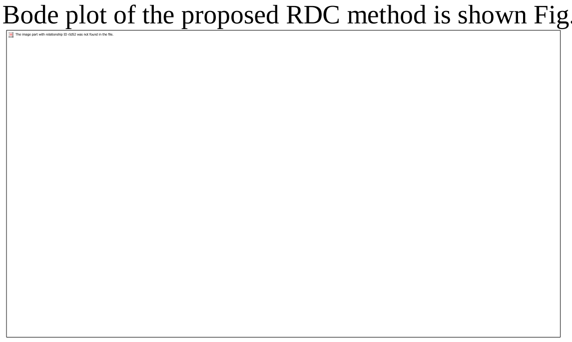

Fig.12: Open loop bandwidth of the proposed RDC

3.2. Procedure for Selecting RDC Bandwidth Components

The ranges of the input carrier frequency (F_C) and the input voltage level to the resolver are in between 47Hz to 30 kHz and $1V_{rms}$ to $1.5V_{rms}$ respectively. The component of gain coefficient (G) is Error Gradient (EG). The EG for a 16bit RDC is expressed as:

EG = Nominal Resolver Input Level x 0.0027

And the gain co-efficient is expressed as

G = 2.22 x Closed loop Bandwidth

G^2 = EG x 0.45 x G_1 x G_2

The recommended value of hysteresis (HYS) for a 16 bit RDC is 1. So the equation to determine the values of the discrete components R_1, R_2, R_3, C_2 and C_3 are given as:

$$R_1 = 6\times10^6 \times EG\times HYS, \quad R_2 = \frac{2}{G\times C_2} \tag{6}$$

$$R_3 = \frac{(25\times10^9)}{G_2}, \quad C_2 = \frac{1}{G_1\times R_1}, \quad C_3 = \frac{C_2}{10}$$

Most of the resolvers have a leading input to output phase shift. The Fig.13 is a simple R-C leading phase shift network, will provide the compensating phase shift required from the resolver reference to the RDC's reference input to bring the signals in phase. If the resolver has a lagging input to output phase shift then an R-C lagging phase shift network (low pass network) is to be required. The R-C phase lead circuit on the input to the demodulator in Fig. 9 is considered when calculating the total system phase compensation.

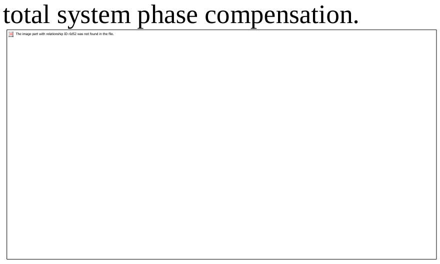

Fig.13: Leading Phase shift network

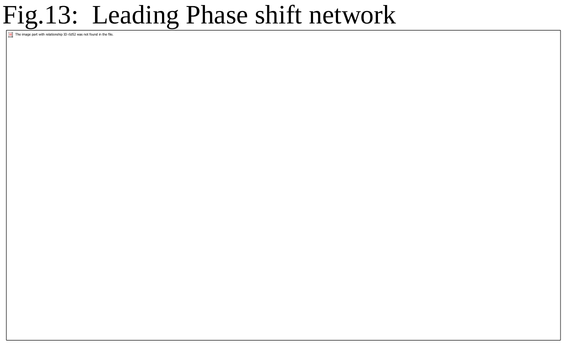

Fig.14: Translation relationship of RDC

The formula for calculating the phase shift network, θ is:

$$\theta = ArcTan\left(\frac{1}{6.28\times F_{ref}\times(R_7+R_8)\times C}\right) \tag{7}$$

4. RESULTS

Based on the procedure, the component values of RDC are evaluated for the following specifications: carrier frequency of 1kHz, nominal resolver input level of

1.5Vrms, resolution of 16 bits, closed loop bandwidth of 50Hz. Maximum tracking rate of 1RPS and hysteresis of 1LSB. For the given specification values, the designed component values for the RDC are: EG=0.00405, G=111, R_1=24.3kΩ, G_2=32768, R_3=762.9kΩ, G_1=1.858, C_2=22μF, C_3=2.2μF and R_2=819Ω. The translation relationship between the position and angle for the designed RDC is shown in Fig.13.

5. CONCLUSIONS

The paper gives an overview of operation principle the resolver and also summarizes the design methods of resolver to digital converters. A novel design method and procedure for calculating the bandwidth of the RDC is presented. In addition, the proposed design method is easily implemented by the simple mathematic calculation. The proposed RDC is simple, small and low-cost.

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