Development of Variable Reluctance Resolver for Position Feedback

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Abstract

The variable reluctance resolver (VRR) is commonly used in the automotive industry as a rotor position sensor. Its use in the Aerospace and Defense Industries has been limited due to inadequate accuracy performance. However, recent interest in the Aerospace Industry for VRRs as a viable alternative to conventional resolvers has driven the development of higher accuracy VRRs for use in angular position feedback applications. This paper presents the progression in the development of the VRR and provides information on the lessons learned during the completion of the first generation of single speed and multi-speed engineering units of VRRs. This first generation of engineering units was evaluated to identify potential design and manufacturing process improvements. Incorporating the lessons learned from the development of the first generation units resulted in an improvement in performance and manufacturability in the second generation of VRRs, making it a desirable option for future use in commutation of brushless DC motors.

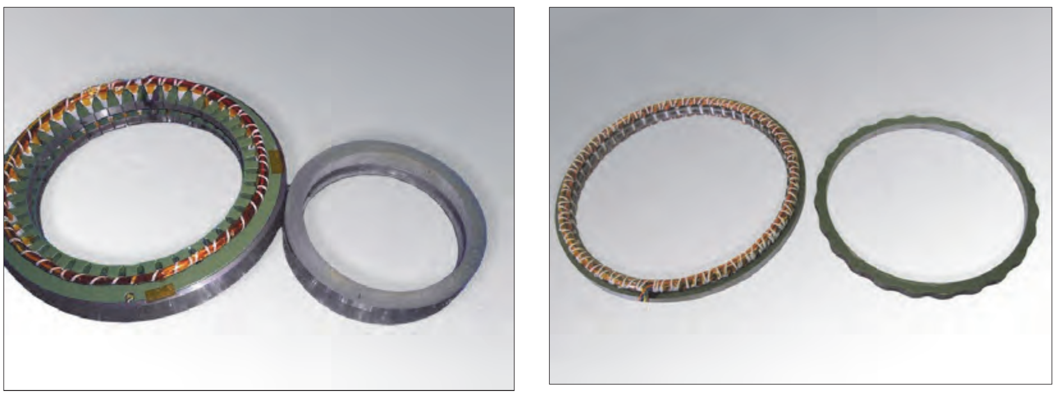

Figure 1. Single-speed (left) and multi-speed (right) variable reluctance resolvers

Introduction

Resolvers are rotary motion feedback sensors used to provide angular position detection in a wide variety of environments; space, defense, automotive and oil exploration. For decades, conventional resolvers have been used for high precision mechanism position feedback and commutation in a range of adjustable speed drives; vector control induction motor, switched reluctance motor and brushless DC motor drives. Besides resolvers, optical incremental encoders and potentiometers offer an alternative solution for position sensing by producing precise incremental position information. However, optical encoders are susceptible to vibration, debris and high temperatures. Potentiometers are easy to use; however the potentiometer contains an electrically conductive wiper that slides across a fixed resistive element causing the possibility of considerable wear. Hence the life cycle of a potentiometer is limited and its sensitivity to vibration is of significance. Resolvers do not depend on moving electrical contacts for signal reliability and do not exhibit significant aging or changes to performance due to extreme temperatures or vibration.

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In addition, conventional resolvers transmit high accuracy angular data electrically in the thousands of a degree (arc-seconds) and consist of a stator, a rotor and a transformer assembly; each with its own winding as seen in Figure 2. Nonetheless, the conventional resolvers are intricate to manufacture and therefore labor intense and costly. Furthermore, in larger conventional resolvers, the transformers have been observed to delaminate and are difficult to rework or replace. The high cost and manufacturing complexity of conventional resolvers lead to the development of variable reluctance resolvers.

Unlike a conventional resolver, the VRR has no need for rotary transformer and it consists of a simpler design. All windings are located on its stator assembly whereas in conventional resolvers the stator core, rotor core, stator transformer and rotor transformer each contain windings as labeled in Figure 2.

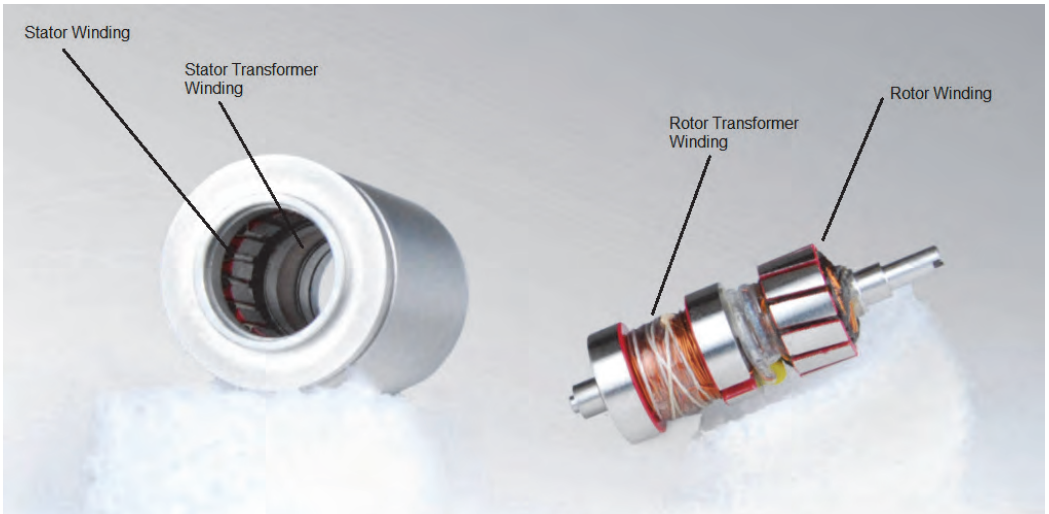

Figure 2. Conventional resolver with transformer

Furthermore, the study and experiments conducted by the Ducommun Team resulted in an improvement in the accuracy of the VRR making them competitive to convention resolvers particularly for the commutation of brushless DC motor drives in the Space and Defense Industries. This paper documents the development and qualification of the VRR for use in commutation of brushless DC motors that minimizes envelope size, mass and increases reliability.

The purpose of development of VRR

1. Provide resolver architecture for continuous operation without rotary transformer
2. Reduce amount of magnetic components and windings
3. Decrease the manufacturing complexity and fabrication cost
4. Reduced envelope size and mass

The VRR was developed to meet the following accuracy requirements:

1. Single speed accuracy to be less than 30 arc-minutes
2. Multi-speed accuracy less than 6 arc-minutes

Background

The VRR consists of stator core and a rotor core and is unique in that its rotor core is slot-less with no windings. Unlike conventional resolvers, the VRR is based on variable reluctance between the stator and rotor segments. The voltages of the output windings of the resolver vary as sine and cosine functions of the rotor angular position. The VRR is structured to vary the reluctance of the magnetic path between the stator and rotor core in accordance with equation (1) through the change in the length of the air gap (l) or the area of the air gap (A). From equations (2) and (3) it is easily determined that the variation in reluctance causes a change in the induced voltage in the sense windings. Therefore, varying the air gap or coupling area will cause a variation in the reluctance and consequently cause a change in the voltage outputs.

$$\mathcal{R} = \frac{l}{\mu A} \tag{1}$$

$$\Phi = \frac{mmf}{magnetic\ reluctance} = \frac{Ni}{\mathcal{R}} \tag{2}$$

$$e = -N\frac{d\phi}{dt} \tag{3}$$

Where $\mathcal{R}$ is the magnetic reluctance; l is the length of the air gap; A is the area of the air gap; Φ is the magnetic flux and e is the induced voltage.

For a multi-pole configuration, as seen in Figure 3, the structure is such that the variation in the length of the air gap between the stator and the rotor produces sinusoidal variations in the output voltages.

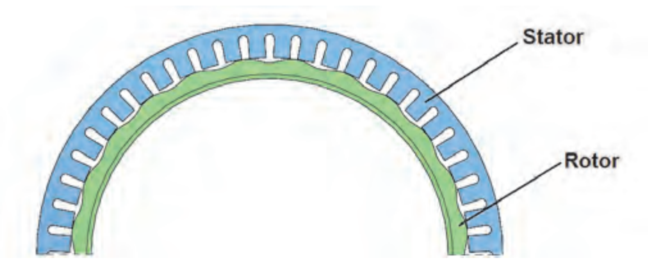

Figure 3. Structure of multi-speed variable reluctance resolver

For absolute position feedback a single speed variable reluctance resolver is used, which consists of a couple-pole configuration. The configuration of a couple-pole VRR varies the reluctance through the variation in the coupling area between the stator and rotor core segments. A unique circular rotor core is supported by two non-magnetic members, as seen in Figure 4. The rotor core provides a diametrical diagonal magnetic path from upper half of stator core to the lower half of stator core as illustrated below.

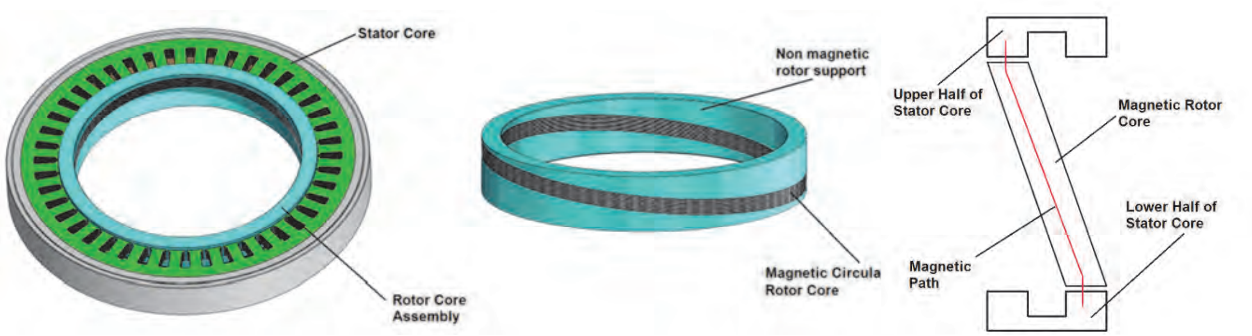

Figure 4. Structure of single-speed VRR

Development of Single Speed Variable Reluctance Resolver

<u>Description of first generation single speed VRR</u>

The architecture of the first generation single-speed VRR, as seen in Figure 5, consisted of two laminated stator cores and a single laminated rotor core. Each stator core, made of high permeability laminations, were stacked, bonded and insulated.

Figure 5. First generation single speed VRR

The two stator cores were then inserted into the back iron and aligned and then bonded to the back iron. The excitation winding was placed between the two laminated stator half cores diametrically, as shown in Figure 6, and the sense winding was inserted through both cores axially.

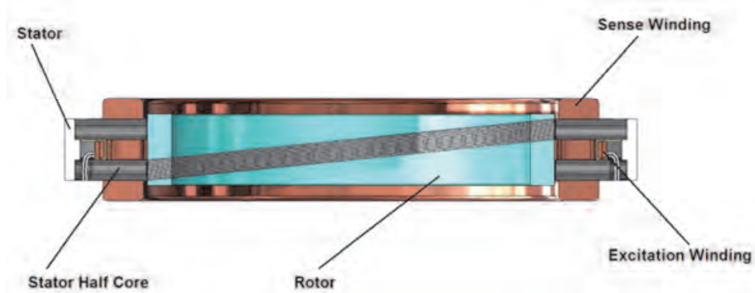

Figure 6. Architecture of the single speed VRR

The rotor core consisted of high permeability laminations, which were stacked and placed on a temporary hub against spacers on either side of the lamination stack and were bonded. The rotor core was designed as a laminated core in order to minimize rotor reluctance since a solid rotor has high reluctance due to eddy current losses. The laminated rotor core produced a high enough transformation ratio of the output voltage to the input voltage.

Shortcomings of first generation single speed VRR

During the manufacturing process and the functional testing, the following were issues which called for design improvements:

- The manufacturing process for the rotor core was extensive and consisted of several machining steps. After the rotor laminations were bonded lamination-to-lamination and lamination-to-spacers, the rotor assembly was machined on the outer diameter (O.D.), then removed from fixture and ground on the inner diameter (I.D.). Finally the rotor assembly was bonded to a hub and its O.D. ground to final dimension to improve concentricity. The several machining processes introduced various stresses to the assembly and jeopardized the bonding adhesive; which introduced de-laminations of the rotor core.
- The thickness of the insulation on the stator cores was inconsistent which contributed to the tolerance stack-up of the stator cores in the stator assembly. Furthermore, the insulation used which was Scotchcast Electrical Resin #260 (3M) was observed to chip off the stator teeth during testing and handling of the VRR.
- During accuracy testing, the accuracy of the single speed VRR was initially found to be approximately 85 arc-minutes as highlighted in Table I, which was much greater than the design

accuracy requirement of 30 arc-minutes. Following the initial accuracy test, various tests were conducted for different parameters to locate which were the greatest contributors to the accuracy of the resolver. The numerous tests included recordings of the signal outputs of the resolver from radial misalignment testing, axial misalignment testing, stator core alignment and repeatability testing. It was established that the stator core alignment had the greatest contribution to the accuracy. See Table I for accuracy readings obtained after the stator core alignment was improved with a significant increase in accuracy from 85 arc-minutes to approximately 48 arc-minutes. For rotor misalignment, the radial misalignment was found to be of higher contribution to the accuracy than axial misalignment with a deviation in the accuracy reading of approximately 9 arc-minutes at the off-set position of 25 µm (0.001 in) as seen in Figure 7.

Table I –Accuracy Test Results of Single Speed VRR

Angle (degree)	0	20	60	100	140	180	220	260	300	340	360
Initial Accuracy Test (arc-min)	0.0	-5.9	-17.8	17.5	44.2	84.4	-40.4	42.6	-48.0	-9.6	0.0
Accuracy after Stator Core Alignment (arc-min)	-0.3	-6.6	-13.1	-2.4	20.1	43.6	47.6	36.3	24.3	7.7	0.3
2nd Gen VRR Accuracy Test (arc-min)	0.0	-9.0	-14.9	-3.4	1.6	-5.3	-9.1	-7.7	6.3	5.6	0.0

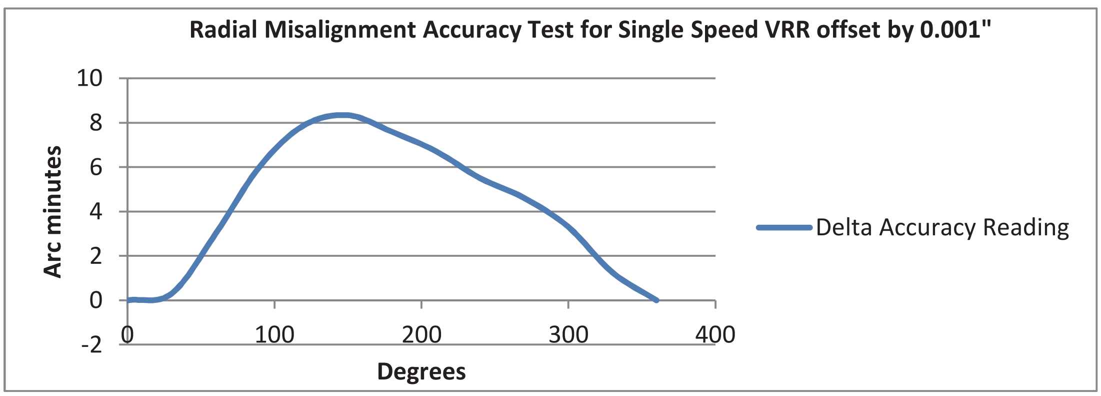

Figure 7. Radial misalignment test result

Lessons learned from the first generation Single Speed VRR

The observations made and the lessons learned from the manufacturing and initial testing of the single speed VRR were the following:

- Excessive machining of the rotor core assembly was causing de-lamination of the rotor core and needed to be dimensioned such as to minimize the machining required to achieve final dimensions.
- Based on the stator core alignment test, it became apparent that the variation in the insulation thickness affected the accuracy significantly; therefore it was found that masking the stator core surface at the outer edge prior to applying insulation was critical.
- Lastly, a final grinding of the O.D. of the rotor core assembly was observed to be necessary to increase concentricity since the accuracy was found to be greatly affected by radial misalignment.

Design improvements for the second generation single speed VRR

The lessons learned from the first generation were implemented in the next generation single speed VRR through the following design modifications:

- The stator and rotor cores were re-designed with the design objective of a solid rotor core in order to eliminate any possibility of de-lamination. This was obtained by increasing the slot area of the stator cores to increase the coil turns in order to compensate for the eddy current losses in the solid rotor and to achieve the required transformation ratio.
- The stator cores were masked at the edges and were electrostatic powder coated using the Scotchcast Electrical resin 5133 allowing for a thinner and more consistent insulation thickness with no chipping observed.
- All machining of the rotor core was minimized by machining the solid rotor core to final dimensions less the O.D. which once bonded to the hub would undergo a minimal O.D. grind to improve concentricity.

The second generation single speed VRR showed significant enhancement in performance once the design improvements had been implemented. Testing of the second generation VRR produced an accuracy reading of approximately 15 arc-minutes as listed in Table I. Comparing to the initial reading of 85 arc-minutes it was a great achievement.

Development of Multi Speed Variable Reluctance Resolver

Description of first generation multi speed VRR

The multi-speed VRR was designed and built with a single laminated stator core with specifically designed tooth profile for optimized sensitivity of variable air gap and a slot-less laminated rotor core. The resolver was developed with an axial length of 6.35 mm (0.250 in) offering a compact design, which resulted in a 30% reduction in mass compared to that of a conventional resolver of similar O.D. The excitation windings and the sense windings were placed on the stator core alone. Its air gap was varied such to produce a sinusoidal change in the magnitude of the output voltages of the two sense windings.

Observations and test results of the multi speed VRR

The performance of the multi-speed VRR was exceptional and produced accuracy test results much higher than required of the design. The short coming of the initial design was limited to the insulation material Scotchcast resin #260 which was chipping as it had in the single-speed VRR.

Accuracy testing was performed and the resolver accuracy was measured in every 1 degree increments from 0 – 360 degrees and its results are summarized in Table II. The highest reading was found at 350 degrees at a value of approximately 35 arc-seconds which is listed and highlighted in the Table. Comparing to the design requirement of 360 arc-seconds (6 arc-minutes) the multi-speed VRR performed much greater than anticipated.

Table II –Accuracy Test Results of Multi-speed VRR

Angle (degree)	0	20	60	100	140	180	220	260	300	340	350	360
Accuracy Test **(arc-sec)**	0.0	36.7	0.1	-21.5	27.9	6.5	-20.5	25.5	3.9	-24.9	35.2	0.0

Conclusion / Summary

The Ducommun team has developed Variable Reluctance Resolvers with sufficient accuracies to be in used in the Aerospace and Defense Industries in angular position feedback applications. The single-speed and multi-speed designs have been fully qualified and were shown to meet internal as well as external customer requirements. The latest development of the variable reluctance resolvers has made them competitive to conventional resolvers and offers an alternative solution in the application of brushless DC motor commutation.