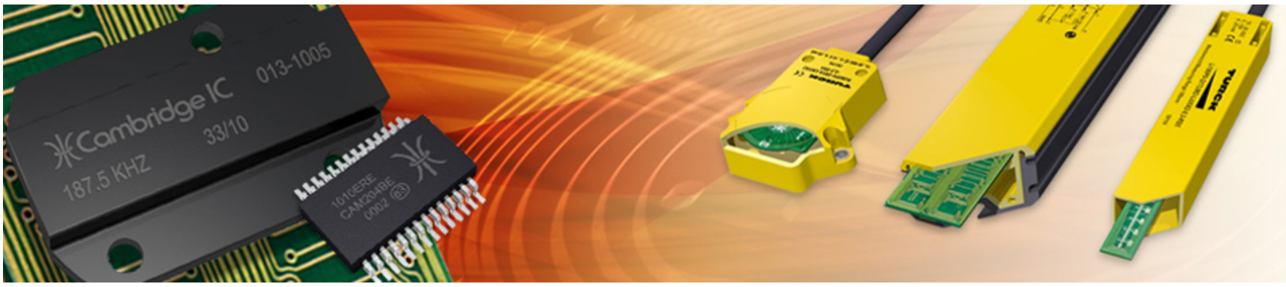


1 Summary

Resolvers are variable transformers having a similar appearance to motors, and they are used to sense angles. Their history dates back more than 75 years, when most applications were military and in aerospace. Their construction is relatively simple and they operate largely without wear and tolerate extreme environments well.

More recently resolvers have become the technology of choice for providing angle and velocity feedback for traction motors, and in particular for automotive applications including electric and hybrid vehicles. This feedback helps control the currents driving the coils of the traction motor, with the objective of high efficiency and smooth operation. Resolver manufactures have responded to cost pressure from the automotive industry by developing simpler types of resolver, in particular variable reluctance. This document compares resonant inductive position sensors to this type of resolver. This is a fairer comparison, because older types of resolver are even more expensive and bulky and are therefore not used in such high quantities.

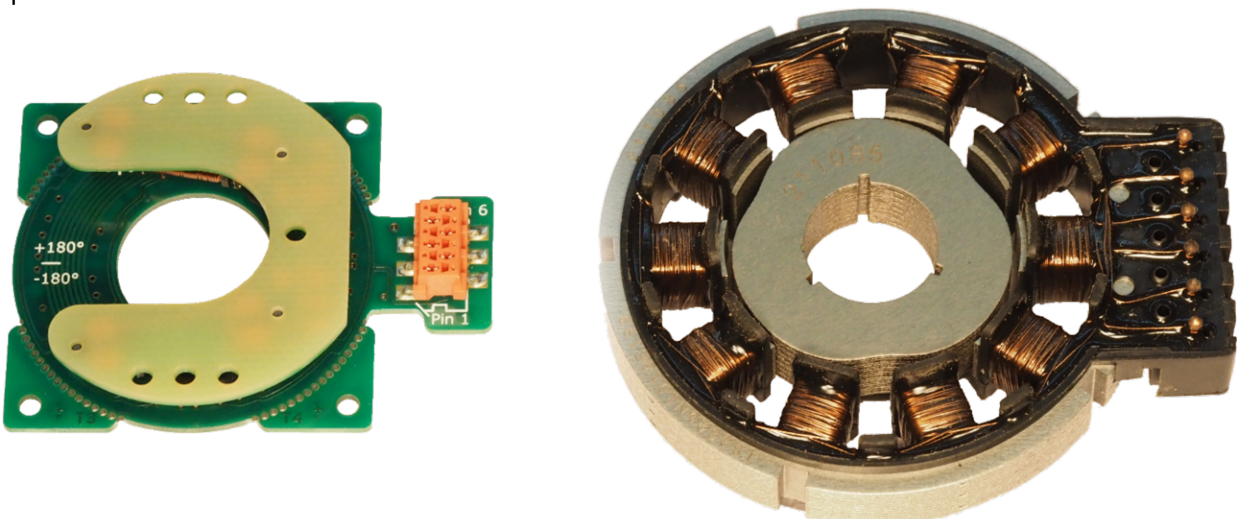


Figure 1 35mm Type 6.3 Rotary Sensor (left) and 52mm VR Type Resolver (right)

CambridgeIC's team has led the development of resonant inductive position sensing technology since 1994. This operates using similar physical principles to resolvers, but it uses printed coils and PCB technology to replace motor-like construction. This delivers…

- Improvements in accuracy, for efficiency and smoothness
- Reduced cost, by using simpler components that are easier to manufacture
- Greater tolerance to misalignment, for ease of installation and lower cost
- Physically smaller parts

This document compares the technologies and explains how these improvements come about.

2 Comparison of Construction

Resolvers operate by magnetic induction. They usually include coils wound around the stator, which is the fixed, non-rotating part with radial arms illustrated on the right of Figure 1. The stator includes transformer steel laminations, which concentrate the magnetic fields for adequately high signal levels. The steel pressings have to be made precisely, because the accuracy of the resolver depends on the magnetic field shapes, which in turn depend mainly on the geometry of the steel parts.

There are typically three coils. One, the primary, is used to energise the stator's steel with a uniformly radial magnetic field. In a VR style resolver, the inner rotating rotor part is shaped with lobes. There are 3 lobes in Figure 1. These lobes concentrate magnetic field in their vicinity so that it flows mainly through the arms of the stator adjacent the three lobes. This shaped concentration of fields is detected by two sensor coils wound around the stator. Their winding density is patterned so that the coupling between rotor and sensor coils is sinusoidal with rotor angle, and repeating 3 times per circle in the case of the part in Figure 1. The other sensor winding is similar, only its coil pattern is shifted a quarter of the lobe pitch so that the resulting sensor signal amplitudes are in phase quadrature (COS, SIN) with mechanical rotation angle.

CambridgeIC's resonant inductive technology is a modern replacement for a resolver. It avoids the use of steel. Instead, the sensor includes planar coils built using a completely standard PCB process. This means manufacture is cost effective and precise. With more freedom to shape magnetic fields by locating coils at optimum locations, it also allows for higher accuracy. A 35mm Type 6.3 Rotary Sensor PCB is shown to the left of Figure 2.

Another aspect of the technology is the use of a resonant target having a high Q-factor. This comprises one or more coils connected to a resonating capacitor to form an inductively coupled resonant circuit. The target for the 35mm Type 6.3 Rotary Sensor PCB is shown to the right of Figure 2. This comprises a 1-layer PCB with two transponder coils and resonator capacitors mounted on it using a standard PCB assembly process.

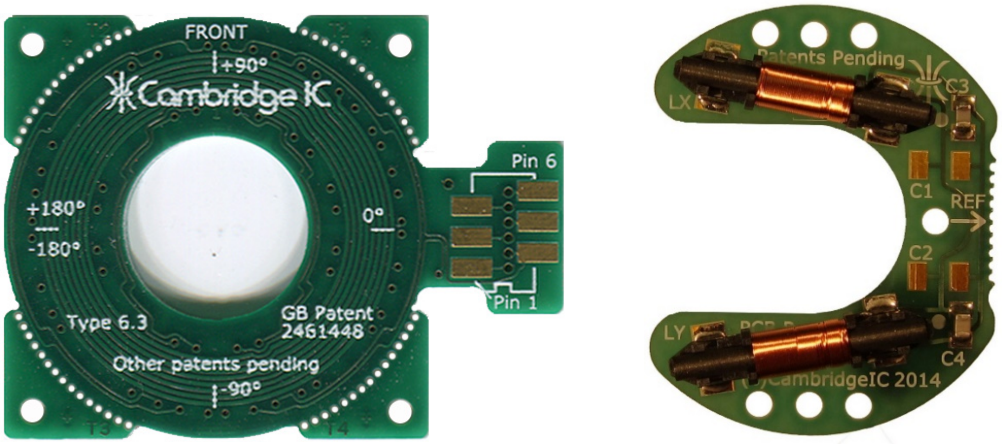


Figure 2 35mm Type 6.3 Sensor (left) and target (right)

35mm Type 6.3 Rotary Sensor includes a coil to excite the rotating target, just like a resolver. It also includes "fine" COS and SIN sensor coils patterned to generate 3 pole pairs of (COS, SIN) waveforms, like the resolver of Figure 1. However there is a further pair of "coarse" sensor coils whose (COSB, SINB) pattern repeats just once per 360° of mechanical rotation.

This allows the processor to determine absolute angle across 360° at all times. When built on a PCB this is a simple addition. To do the same on a resolver involves a dramatic increase in complexity and size, and increases errors. It is usually avoided.

The target's two transponder coils generate both a 3 pole pair magnetic field and a 1 pole pair field, for coupling with both fine and coarse sensor coils. The exact angle and location of the transponder coils is designed to maintain the fine sensor coils' (COS, SIN) relationship with angle even when the target is misaligned both radially and axially. This optimisation is not possible with a resolver, because there are not enough design parameters available to optimise the design in the same way.

3 Comparison of Electronic Processing

Both types of sensor are connected to an electronic processor. This…

- Energises the excitation coil,
- Detects and measures the signals returned by the sensor,
- Calculates angle, and
- Communicates measurements to a host device

Resolver processing can take place inside a dedicated chip such as the Analog Devices AD2S82AHPZ. Alternatively, a general purpose DSP chip may be used with special processing algorithms implemented in software, such as in TI's TIDA-00796 reference design.

Resonant inductive processing takes place inside one of CambridgeIC's Central Tracking Unit (CTU) chips. The CAM502 is the normal choice when replacing a resolver due to its fast response. The CAM312 can be considered for slower moving applications.

Resonant inductive sensors are more complex to process than a resolver. Key challenges include…

- Higher operating frequency,
- The need to detect and lock onto the resonant frequency of the target, rather than operating at a fixed resonator frequency,
- Pulse echo detection instead of continuous (see below),
- Coping with a variable and dynamic detection phase,
- Combining information from both fine and coarse sensor coils to deliver a full 360° absolute output

CambridgeIC's CTU chips use pulse echo detection, which separates the excitation of the target from its detection. This is only possible when the target includes a resonator with high Q-factor, so does not apply to processing resolvers. The procedure is illustrated in Figure 3. The CTU chip first energises the excitation coil – the "pulse". Then it detects the "echo" signal from the sensor coils once the excitation is silent.

The advantage of pulse echo detection is that the system is absolutely insensitive to direct coupling between excitation and sensor coils. This direct coupling is a major source of angle error in resolvers. However it is completely absent in CambridgeIC resonant inductive sensors, helping to deliver a dramatic performance improvement.

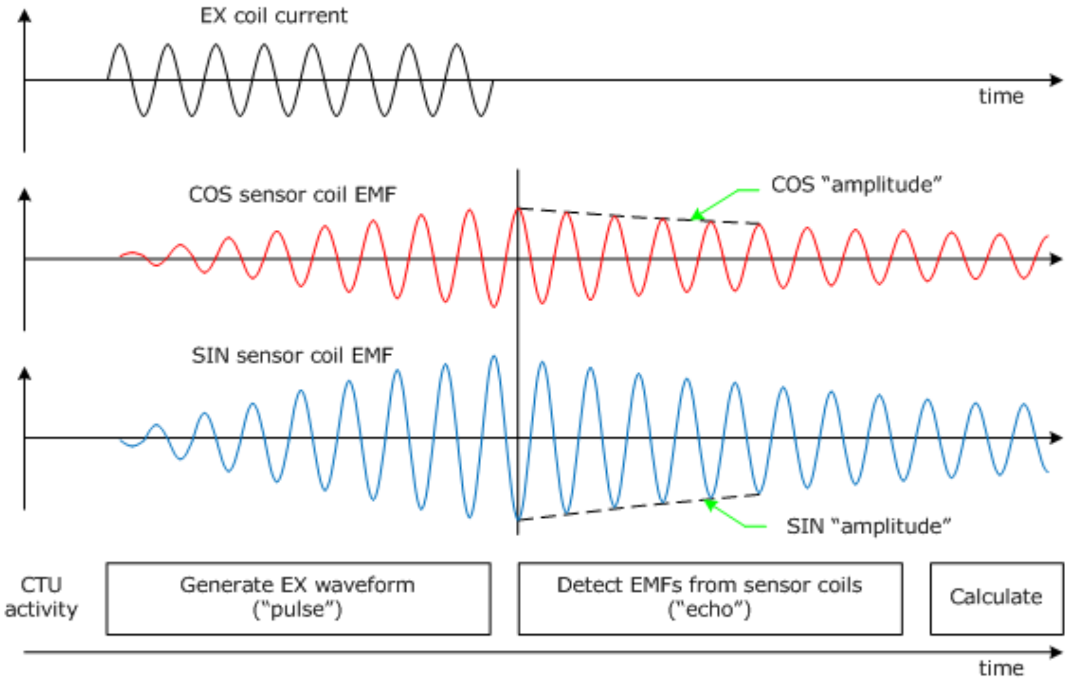


Figure 3 Pulse echo detection for resonant inductive sensors

4 Performance

Figure 4 compares the accuracy of the two sensors illustrated in Figure 1: a 35mm Type 6.3 Rotary Sensor from CambridgeIC and a 52mm VR Type resolver.

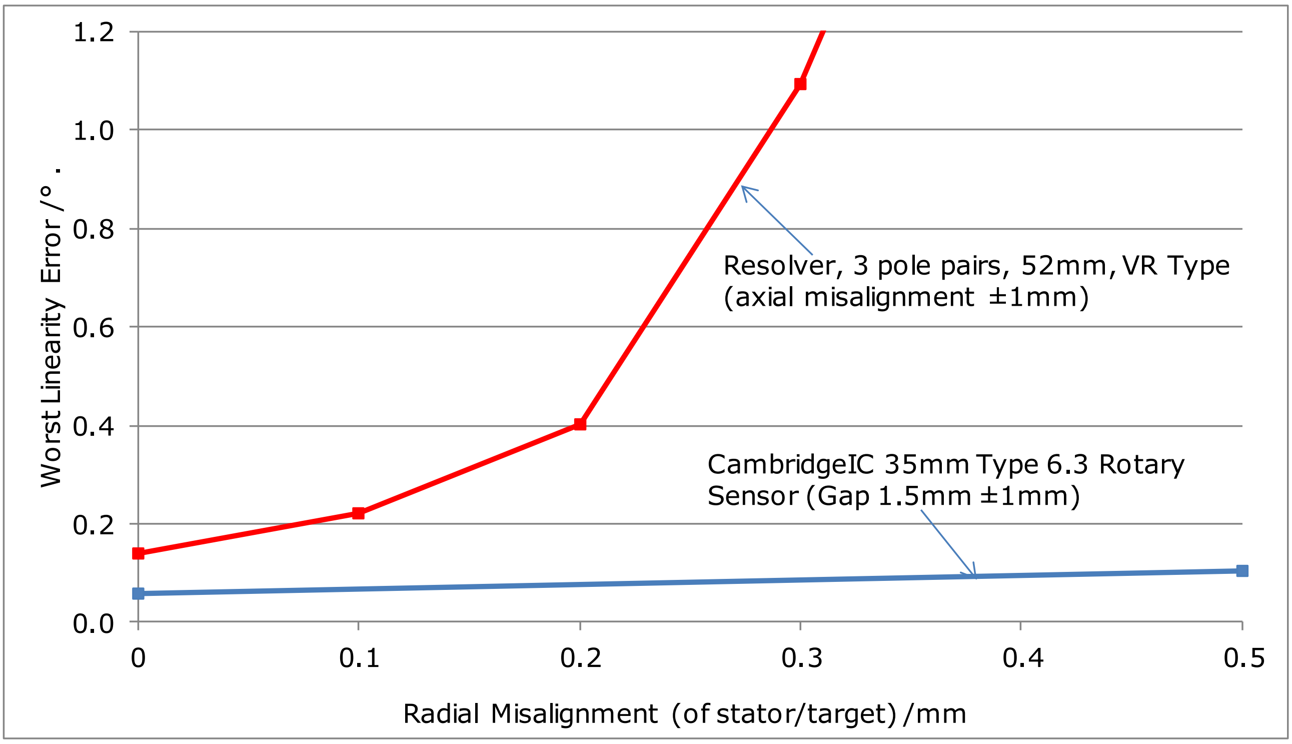


Figure 4 Linearity Error comparison, typical parts

In both cases the x-axis of the graph is the misalignment of the rotation axis relative to the sensor. The y-axis is the linearity error, which is the accuracy once offset error and noise have been removed.

The target and rotor are well aligned with the rotation axis. Results for the resolver would be much worse if the rotor were misaligned relative to the rotation axis.

The resolver was connected directly to precision test equipment (HP89410A vector analyser), which energised the resolver and performed detection at the 10kHz. In-phase and quadrature measurements were sent to a PC which resolved the signals to the optimum phase for accuracy and performed position calculation. This approach means that the results for the resolver in Figure 4 do not include the additional errors associated with real-world processing electronics.

The 35mm Type 6.3 Rotary Sensor was processed with a CambridgeIC CTU Chip (results for the CAM502 and CAM312 are similar). This means that the results for the 35mm Type 6.3 Rotary Sensor in Figure 4 DO include errors associated with real-world processing electronics.

The 35mm Type 6.3 Rotary Sensor and target can be mounted with 0.5mm radial misalignment between their axes. The chosen resolver's accuracy deteriorates so quickly with misalignment that a practical limit is much smaller, perhaps 0.2mm. With 0.2mm misalignment, the resolver's error is ±0.4°, which is 4 times worse than the 35mm Type 6.3 Rotary Sensor with 0.5mm misalignment.

5 Implications for Motor Control

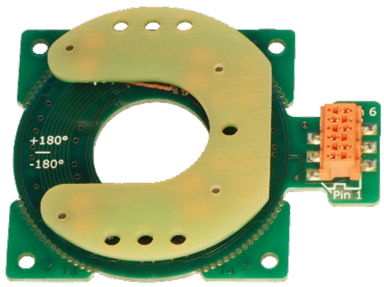
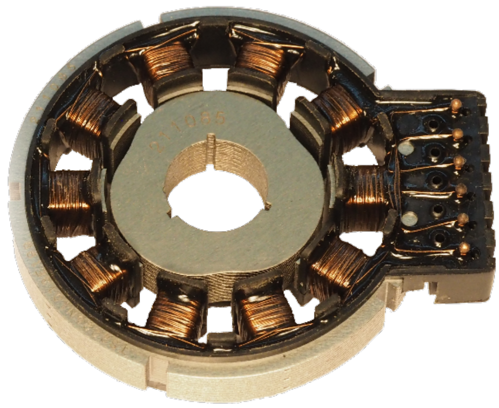
Typical applications for both sensors include providing feedback for control of an electric vehicle's traction motor.

Angle feedback is used to ensure accurate motor commutation, to ensure the current flowing in each phase of the motor is always optimised for efficiency. The greater accuracy of CambridgeIC's resonant inductive sensor system means greater motor efficiency.

Motor control systems also use angle feedback for calculating velocity, by calculating the rate of change of angle. The errors shown in Figure 4 yield substantial velocity error for the resolver. A system using a CambridgeIC resonant inductive sensor system will have dramatically lower velocity error, by virtue of the lower angle error. In addition, it is easier for the motor control system to take account of remaining reproducible angle errors, because the sensor system output is absolute across 360° rather than repeating every 120°.

Traditional resolver processing methods result in a big time lag between actual angle and reported angle. This is due to the much lower operating frequency of a resolver, and the filtering required inside the processor for obtaining adequate resolution. This lag can be largely eliminated by processing techniques which compensate reported angle for processing delays, based on a knowledge of velocity. An alternative technique is model based filtering, where the resolver includes a resolver model with its delays and a control loop which aims to match model and measurements, to obtain a lag free result. However in both cases, it is only Phase Delay that is eliminated. This is adequate when velocity is constant and the control loop bandwidth (responsiveness) is low. However when there are changes in velocity Group Delay is the critical parameter, measuring the delay in detecting a change in velocity. CambridgeIC's CAM502 chip has a Group Delay of only 130µs. Resolver processors, even ones with zero phase delay, have many times this Group Delay. They are therefore less able to provide speed feedback in highly dynamic systems.

6 Side by Side Comparison

	CambridgeIC Rotary Sensor (35mm Type 6.3)	**Resolver (52mm VR Type)**
Appearance		
Sensor construction	Conventional 6-layer PCB	Precision steel laminations, wire windings, mouldings
Target construction	1-layer PCB with 2 SMD capacitors and 2 SMD coils	Precision steel laminations
Mass	6g	84g
Outer diameter	35mm	52mm
Thickness	8mm (with 1.5mm gap)	14mm
Processor for test	CAM204 or CAM502 IC	HP89410A vector analyser
Max Radial Misalignment	0.5mm	0.2mm
Error at Max Radial Misalignment	± 0.1°	± 0.4°
Group Delay actual → reported angle	130µs (CAM502)	Several times 100µs (1 cycle of 10kHz) depending on filtering
Angle range	Full 360°	Incremental (e.g. 120° repeat)

Typical benefits from using a CambridgeIC resonant inductive sensor in place of a resolver in motion control applications include…

- More accurate, typically resulting in greater efficiency and smoothness
- Much smaller Group Delay, for control stability in highly dynamic systems
- Do not require precise installation because they tolerate misalignment much better
- Full 360° output
- Less space required
- Lower overall cost
- Sensors and targets are PCBs which can be built by the customer’s own contract manufacturer

7 Find out more

This white paper is intended to provide background and guidance; for more detailed insights and assistance with questions on resonant inductive sensing and whether it is suitable for your application, contact CambridgeIC's engineers, using the details below.

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9 Legal