Electrical design considerations for industrial resolver sensing applications

Texas Instruments

Ankur Verma
Applications Engineer

Brian Rodriguez
Product Marketing Engineer

Mixed Signal Automotive
Texas Instruments

Resolver sensors in harsh environments help to achieve accurate angular position and velocity data.

Resolver sensors are mechanical or analog sensors that can determine the absolute position and velocity of a motor. These sensors are commonly used in industrial, automotive and aviation applications – specifically in “harsh” environments when a motor or sensor could be potentially exposed to contamination.

Examples of common contaminants include oil, dirt, food particles, or even extreme temperatures where other rotary sensing technologies could fail. There are unique design challenges and requirements based upon specific end products, and several are common among most industrial applications. Two of these challenges are: 1) the absolute accuracy of the angular position and velocity data, and 2) minimizing/eliminating electromagnetic interference (EMI).

Industrial applications for resolver sensors

Many times, absolute rotary sensing technologies such as optical encoders are chosen for industrial applications. However, resolver sensors are ideal when conditions are rugged or when a low-cost alternative is preferred. Servo motors are frequently used within industrial applications where a servo drives the interface with the resolver sensors, as well as other types of position sensors. Applications that commonly use servo motors and servo drives in combination with resolvers to measure angular speed and position include:

- Computer numerical control (CNC) and injection molding machines
- Elevators/lifts
- Robotic arms
- E-mobility products (electric bikes, scooters, wheelchairs, and many others)
- Rail transport
- Agricultural and construction equipment
- Buses and heavy trucks
- Golf carts and low-speed electric vehicles

Key resolver sensing system requirements

Accurate and timely resolver angle output

Before addressing methods to mitigate the effect of EMI in an industrial system utilizing a resolver, it is important to understand why accurate position control is essential. Resolvers provide an analog output with, theoretically, infinite resolution. The analog-to-digital conversion technology limits the resolution by how well it divides output into chunks or steps. This finite division from the continuous angle results in a quantization error. For example, you can use a 12-bit resolution converter to give an angle output. One revolution of the shaft gets divided into 4096 parts (2^12 for a 12-bit resolution). Since there are 60 minutes in one degree, there are 21600 arc minutes (arcmins) in one revolution (60 x 360). The steps are spaced 5.27 arcmins apart (21600/4096). The system cannot provide information better than 5.27 arcminutes!

Two key areas for determining correct angle position are system accuracy and system settling time. The latter basically is how long it takes for the angle output to show an accurate position. Every component in the system needs to be evaluated to determine the limiting factor. Typical error accuracy in the system is the sum of the resolver and the resolver analog-to-digital conversion's (RDC's) architecture error.

Most commonly, a resolver error can be from 3-10 arcmins. Adding the RDC's conversion error of 5.27 arcmins (taken from above), gives us 8.27-15.27 arcmins. Thus, choosing the right RDC is important. Provided is a list of items that can affect accuracy and settling time in a typical resolver application [1]:

Mechanical

- Sensor construction (for example, null voltage, transformation ratio)
- Sensor specifications vary over temperature
- Coil imbalance: sine and cosine coil output voltages could be imbalanced, resulting in an error
- Misalignment of resolver sensor: resolver may be incorrectly mounted, leading to a system static error
- Number of poles in the resolver sensor: increasing poles reduces angular error since the angle detected is 360 degrees mechanical per the number of pole pairs

Electrical

- Resolver analog-to-digital conversion architecture
- Time delay between the input of the resolver signal to the angle output, settling time
- Imbalance between analog front-end (AFE) components
- System's ability to handle environmental factors (for example, external magnetic field or common-mode noise)

Settling time

When the resolver's motor position or the output signal changes rapidly, settling time is a quick performance indicator of the RDC's control system [2]. **Figure 1** shows a settling-time example of an RDC feedback control system with a step-input change (black line). The blue signal shows normal-mode response for the circuit and the red signal shows response during acceleration mode (rapid change in angle). In order to follow the rotation angle under rapidly changing conditions, the acceleration mode helps the control loop to easily track a fast rotation angle [3].

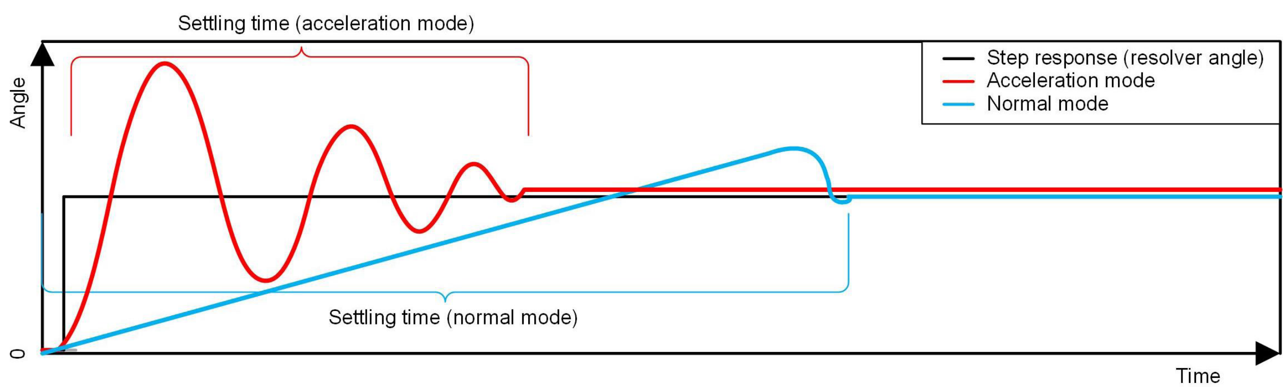

***Figure 1**. RDC step response settling time.*

EMC/EMI impact resolver systems

Electromagnetic compatibility (EMC) refers to how an electronic system can operate within an electromagnetic environment without problems (immunity). Similarly, system emissions must not disturb any product in its locality (emission). In industrial equipment applications, the variable-speed drives and its control circuit can be a major source of interference. The fast switching of power components, such as insulated-gate bipolar transistor (IGBTs) and microcontroller, are major sources of high-frequency emissions or interference. IGBT switching time can be as high as 100 nS.

Electrical equipment should be immune to high-frequency phenomena, such as:

- Electrostatic discharge (ESD)
- Fast transient burst (also known as EFT)
- Radiated electromagnetic field
- Conducted RF disturbance
- Electrical surge

Limitations are determined by industry standards, such as IEC61800-3. IEC61800-3 specifies EMC requirements for variable-speed drives consisting of AC/DC motor and its control circuitry. Certain basic electrical design principles should be followed for any design in such an environment to mitigate the effect of noise [4].

Electronic PCB schematic and layout design

- Route power and analog grounds separately
- Use analog filters to eliminate common-mode noise on sensor signals
- High-frequency, low-impedance filters for high-frequency disturbances such as ferrite beads
- Minimize loop areas so that ground offers as low impedance as possible to the signal return path

Mechanical Design

- Use shielding in cables and connectors (such as shielded DB-9).
- Wire routing: minimize cable length between the drive and sensor component
- Use shielded twisted-pair power and control cables to avoid disturbances.
- Use double shielding to reduce radiated emissions

Immunity requirements for variable-speed drives

TI engineers tested against the IEC61800-3 standard for environment specifications (Table 1). This Design uses shielded connectors and shielded cables >30 m.

Environment 2				
Connector	**Test for**	**Reference**	**Levels**	**Criteria**
Cabinet/case	ESD	IEC61000-4-2	4 kV (8kV) CD or 8 kV (15 kV) AD 1)	B
	Radiated RF	IEC61000-4-3	80-1000 MHz, 10 V/m, 80% AM (1 kHz)	A
Interfaces for control signals and DC auxiliary supplies <60 V	EFT	IEC61000-4-4	±2 kV (4 kV)/5 kHz, capacitive coupling	B
	Surge 1,2/50 µs, 8/20 µs	IEC61000-4-5	±1 kV (2 kV) for shielded cable at shield (2 Ohm/500 A) min. 20 m cable length.	B
	Conducted RF	IEC61000-4-6	0.15-80 MHz, 10 V/m, 80% AM (1 kHz)	A

***Table 1**. IEC61800-3 EMC specifications for variable speed drives.*

The definition of criteria is given in Table 2.

Class	Performance (pass) criteria
A	The module shall continue to operate as intended. No loss of function or performance even during the test.
B	Temporary degradation of performance is accepted. After the test, the module shall continue to operate as intended without manual intervention.
C	During the test, loss of functions accepted, but no destruction of hardware or software. After the test, the module shall continue to operate as intended automatically, after manual restart, or power off, or power on.

***Table 2**. EC61800-3 standards for pass performance.*

Where do EMI results come from?

Any high dI/dt or dV/dt can be a significant potential source of EMI. The edge rates of the digital signal can create harmonics and intermodulation distortion. For example, take a 10 MHz square wave with a 10 ns edge rate on one side, and a 1 ns edge rate on the other. This demonstrates how the increased harmonics content accompanies the square wave with faster edges. Use equation 1 as a rule of thumb to determine the frequency extent of harmonics at a particular rate:

$$f_{\max} = (\pi * t_{rise})^{-1} \quad (1)$$

This equates to about 31.8 MHz for the 10 ns edge rate. **Figure 3** shows that the last significant harmonic occurs at 30 MHz. Meanwhile, the 1 ns edge rate example equates to a maximum frequency of 318 MHz (**Figure 2**). If the frequency scale is extended beyond 300 MHz, it shows that the harmonics are also significant, but diminish rapidly above that frequency.

These methods can help to reduce the overall impact of noise on the resolver system's accuracy:

- Using differential signaling helps to mitigate electrical noise in the cable
- Shielded wires couple noise into the ground before they affect sensor circuit and produce errors
- AFE used in RDC architecture filters out common-mode noise
- Strive for a near-perfect ground with as low impedance as possible
- Minimize loops that can act as EMI antennas

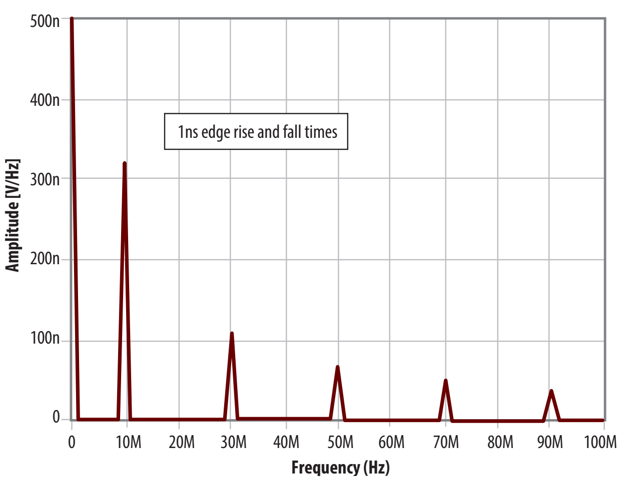

***Figure 2**. Frequency spectrum for a 10 MHz square wave.*

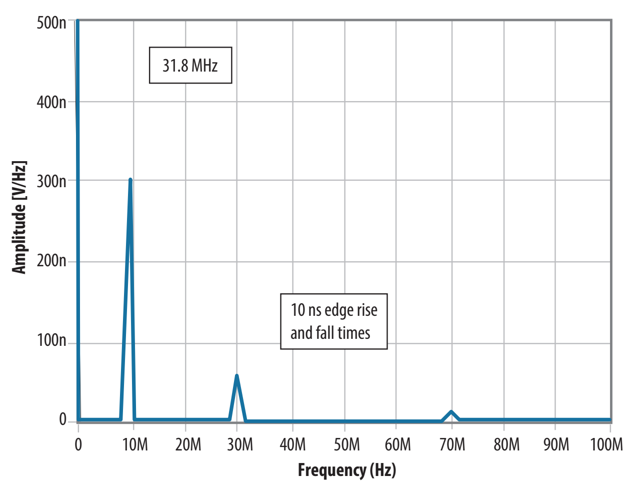

***Figure 3**. Frequency spectrum for a 31.8 MHz square wave.*

Shielding and filtering

All conductive parts such as cabling, earth, metal enclosure and such things can spread the emissions. The cable's transfer impedance must be less than 100 mΩ/m in a frequency range of up to 100 MHz. The highest shielding effectiveness is achieved with a metal conduit or corrugated aluminum shield. The longer the cable run, the lower the transfer impedance required. Common-mode inductors can be used in signal cables to suppress common-mode disturbance signals above a certain frequency. An ideal common-mode inductor does not suppress a differential-mode signal. The Faraday Cage technique is another common method for controlling radiated emissions.

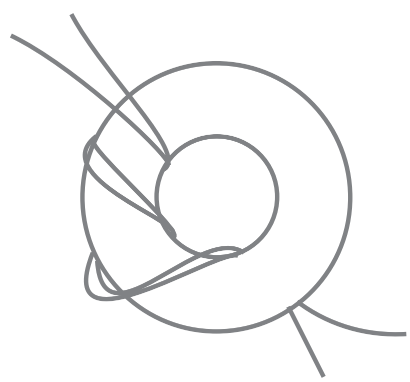

***Figure 4**. Example choke to suppress common-mode noise.*

Conclusion

The unique high-accuracy and noise challenges presented in industrial motor position sensing applications can be addressed with thorough design consideration and careful selection of electronic components. When designing with resolver sensors, a designer should consider the specification of settling time, the IC's performance with regards to EMI/EMC, and how these affect the overall system accuracy.

References

1. Verma, Ankur; Chellamuthu, Anand. "Design considerations for resolver-to-digital converters in electric vehicles," Texas Instruments Analog Applications Journal, 1Q 2016
2. Ahmed, Irfan. "Implementation of PID and Deadbeat Controllers with the TMS320 Family" (SPRA083), TI Application Report, 1997
3. Mancini, R. "Op Amps for Everyone," ISBN: 978-0-7506-7701-1. Elsevier 2003
4. Staebler, Martin. "Designing an EMC-compliant interface to motor position encoders – Part 1," TI Motor Drive Control blog, August 31, 2015

Additional Reading

- Verma, Ankur; Panacek, J. "PGA411-Q1 PCB Design Guidelines," Texas Instruments Application Report (SLAA697), March 2016
- Verma, Ankur; Xu, F. "Troubleshooting Guide for PGA411-Q1," Texas Instruments Application Report (SLAA687), February 2016
- A. Verma, F. Xu, J.Panacek. "PGA411-Q1 Step-by-Step Initialization w/ any Host System, SLAA688)" Mar'16, TI Application Report, March 2016
- Download the PGA411-Q1 data sheet

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265