Observer-based Resolver Conversion in Industrial Servo Systems.

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Abstract

Resolvers are commonly used in industrial servo systems. The conversion of resolver signals to measure position is usually accomplished using a tracking loop which causes phase lag between the actual and measured positions. This phase lag causes instability in the control loop and ultimately reduces performance of the servo system. Observers are well known to reduce phase lag caused by sensors. Observers in servo systems use a combination of the position signal and the torque producing current to observe the motor speed. Resolver-to-digital converters (RDCs) have a structure similar to observers so that RDCs can be modified to behave like observers. This provides several advantages including providing position and velocity feedback with little or no phase lag, and providing estimations of motor acceleration and torque disturbance. Acceleration feedback can be used to reduce problems with mechanical resonance. Torque disturbance feedback can be used to improve the dynamic stiffness of the control system.

Introduction

Resolvers are multi-winding transformers in which the transformer ratio varies with position. The signals from the resolver are processed to generate a position signal; this process is commonly called “resolver-to-digital conversion” or RDC. RDC is usually structured in a tracking or “double integrating” loop. This loop acts like a filter, reducing the magnitude of high-frequency noise, but also generating lag between the actual position and the RDC output. Phase lag within a control loop is well-known to have harmful effects such as reducing stability margins, and forcing servo gains to be lowered; ultimately, this phase lag can reduce machine performance.

The use of observers is known to improve the performance of servo controllers. Observers combine knowledge of the plant operation and feedback signals to derive more knowledge of plant states than can be measured from the feedback device alone. A traditional tracking RDC can be restructured as an observer. By combining knowledge of the operation of the servo system with feedback from the resolver, the observer reduces the phase lag of RDC. In addition, the observer can be used to derive motor acceleration and disturbance torque. Acceleration feedback can be used to reduce problems with mechanical resonance. Torque disturbance feedback can be used to improve the dynamic stiffness of the control system.

Resolvers and traditional RDC

Resolvers are commonly used as position sensing devices. Also, most modern controllers derive velocity feedback from the position sensor by taking the difference of the two most recent positions. Resolvers used in industry fall into two major categories: housed and frameless, both of which are shown in Figure 1. 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. Resolvers have several advantages, the most important of which are low cost, rugged construction, and very high reliability.

![Figure 1. Example a) housed and b) frameless resolvers](image)

The electromagnetic interaction between the rotor and stator provides signals from which position can be derived. Resolvers have three windings: a reference, a sine feedback, and a cosine feedback. The reference is a fixed sinusoidal signal, typically with a magnitude of 4 – 8 volts and a frequency of 4kHz – 10 kHz. The resolver behaves like a pair of rotating transformers. The transformation ratio from the reference winding to the two feedback windings varies with the position of the resolver rotor. Assuming a reference of \(\sin(2\pi f t)\), the SIN
winding will be \( \sin(2\pi 5000t) \times \sin(\text{PRES}) \) where \( \text{PRES} \) is the resolver-rotor position. Similarly, the COS winding value will be \( \sin(2\pi 5000t) \times \cos(\text{PRES}) \). This is shown in Figure 2.

**Figure 2. Resolver and R/D converter wiring**

### Converting the signal

The resolver provides signals that must be processed in order to derive motor position. The traditional RDC is a single monolithic chip that implements a variety of digital and analog functions. As depicted in the conceptual diagram of Figure 3, the SIN and COS signals are demodulated to create the signals \( \sin(\text{PRES}) \) and \( \cos(\text{PRES}) \). Simultaneously, the estimated position, \( \text{PRD} \), which is stored in an up/down counter, is fed to specialized D/A converters which produce the signals \( \sin(\text{PRD}) \) and \( \cos(\text{PRD}) \). These signals are multiplied to produce the signal \( \sin(\text{PRES}) \times \cos(\text{PRD}) - \sin(\text{PRD}) \times \cos(\text{PRES}) = \sin(\text{PRES} - \text{PRD}) \). Assuming that the position from the RDC and of the resolver are fairly close together, \( \sin(\text{PRES} - \text{PRD}) \approx \text{PRES} - \text{PRD} \). In other words, this signal represents the error between the actual position and measured position.

A PI compensator is applied to the error signal, \( \sin(\text{PRES} - \text{PRD}) \). This is usually an op-amp circuit with gains set by discrete resistors and capacitors. The compensator output, which is an analog signal, is converted to a pulse train through a voltage-controlled oscillator or VCO. The output of the VCO is fed to the up/down counter, which acts like an integrator, summing the VCO pulses over time.

**Figure 3. Simplified RDC**

The RDC of Figure 3 is redrawn in Figure 4 to emphasize the effects of the conversion process on the servo system. In Figure 4, the demodulation and trigonometry are combined to create a signal representing the actual position of the resolver, \( \text{PRES} \). This signal is compared to RDC position, \( \text{PRD} \), to create an error. That error is PI-compensated and fed to an integrator to create \( \text{PRD} \). Note that in the traditional RDC, the signal \( \text{PRD} \) does not explicitly exist. However, dynamics of the RDC are represented accurately in Figure 4.

**Figure 4. Idealized structure of R/D conversion.**
Figure 4 can be used to derive a transfer function of the RDC using the $G/(1+GH)$ rule [3]. Assuming that
demodulation and trigonometric functions do not significantly affect the dynamics (a reasonable assumption), the
relationship between the actual resolver position and the output of the RDC is:

$$P_{RD}(s) = \frac{s \times K_{PRD} + K_{IRD}}{s^2 + s \times K_{PRD} + K_{IRD}}$$

(1) shows that the RDC behaves like a 2nd order low-pass filter. At low frequencies, where the $s^2$
denominator term is overwhelmed by the other terms, (1) reduces to one; so, at low frequency, the converter
generates no significant effects. However, at high frequencies, the $s^2$ term will become larger, inducing
attenuation and phase lag. Drive manufacturers are responsible for selecting and installing the components that
set the PI compensator gains. They normally try to maximize the gains in order to raise the effective bandwidth
of the RDC, which minimizes the phase lag induced by the process. However, stability margins and noise
combine to limit the bandwidth so the typical RDC has a bandwidth of about 600 Hz.

The main problem caused by induced phase lag of the RDC is the reduction of phase and gain margins in the
control system [3]. For high-performance systems, the phase lag of an RDC can cause stability problems such as
overshoot and ringing. Ultimately, this can force the reduction of gains, lengthening response times. For
example, based on tests carried out by one of the authors, the phase lag induced by RDC limited the velocity-loop
bandwidth to about 125 Hz. The removal of the RDC phase lag allowed the bandwidth to be increased to almost
200 Hz while maintaining the same stability margins. For high-performance servo systems, the phase lag of an
RDC can be a significant barrier [3].

It should be stated that most of the processes of RDC can also be executed in software [4]. The trigonometry
of Figure 3 may be replaced with an inverse tangent function and the VCO and up/down counter can be replaced
with a software integrator [5]. Software RDC provides many advantages including reduction in hardware cost
and allowing the end user to modify the RDC compensation gains, say, lowering them to attenuate noise.
However, the operation of the conversion loop is similar and the dynamics of both are equivalent.

Observers

Observers are commonly used to determine internal states of a system based on measurements of other states.
Observers are often applied in cases where the observed states cannot be measured because mounting a sensor is
either impractical or too expensive. Observers can also be used simply to improve the quality of measured
signals. For example, a resolver measures motor position, but in doing so, it adds considerable phase lag and an
observer can remove this lag. This is how the observer will be used here.

The Luenberger observer [6, 7, 8, 9], as shown on the right side of Figure 5, observes a state by combining
two sources of information: the sensor output ($Y(s)$) and the power converter output ($PC(s)$). Consider first the
path from the power converter (the current controller) which produces a power output that drives the physical
system (the motor) which feeds the actual state, $C(s)$; the actual state feeds the actual sensor to produce a sensed
output, $Y(s)$. Simultaneously, the power converter output is applied to the model or “estimated” plant ($GPEst(s)$),
which produces an observed state, $C_O(s)$, which feeds a model sensor. The model sensor produces an observed
sensor output, $Y_O(s)$. This path is often called the “prediction” path because it predicts where the state will go
based on the power applied to the plant.

Ideally, the prediction would be sufficient for producing a high-quality estimate of the actual state.
Unfortunately, there are numerous sources of error that degrade that signal. For example, disturbances unknown
to the model system affect the actual state. In addition, the plant and sensor models are not exact replicas of their
physical counterparts. These errors corrupt the observed state. The second path in the observer, often called the
corrector path, improves the quality of the observed state.

The corrector path runs from the rightmost summing junction in Figure 5 through the observer compensator.
That summing junction compares the outputs of the actual and observed sensors to produce observer error. That
error is fed into an observer compensator, typically a PID compensator. The compensator output is added to the
power converter output before it feeds the model plant. The high-gain observer compensator drives the observer
to error to near zero so that the actual and observed sensor outputs are nearly identical. If the sensor model is
accurate, this forces the observed state to follow the actual state. The observer of Figure 5 produces, $C_O(s)$,
which is used to close the control loop in place of the sensed output, $Y(s)$.
The benefits of an observer can be understood by considering that the observed state is formed with two signals: the power converter and sensor outputs. A transfer function can be built to show that the observed state relies on the sensor at low frequencies and the power converter output at high frequencies [6]. By adding the power converter output, the observer eliminates the phase lag caused by relying on the sensor. This will be important later when the RDC structure is improved.

Applying the observer to RDC

The RDC process from Figure 4 is redrawn in Figure 6a. Here, the blocks are rearranged into a style similar to an observer. A factor of 1/s is removed from the RDC compensator and moved forward to a separate block. Notice that the RDC compensator appears in the same position at the observer compensator (GCO(s)) in Figure 5. Notice also that the first factor of 1/s appears in the position of the model plant (GPEst(s)) and the second 1/s term appears in the position of the model sensor (GSEst(s)).

The RDC based on an observer structure is shown in Figure 6b. Here the traditional RDC structure is augmented with the output of the power conversion, IF. In this structure, the torque-producing current predicts the effects of the motor current on the motor velocity before those effects can be measured with the RDC. This reduces or, in some cases, even eliminates the phase lag caused by the RDC. One other modification is that a third term, KIIRD, is added to the observer compensator. This term is used to remove offset that would otherwise be added to by power converter output.

The output of the observer is affected by the accuracy of the model (here, of KT/J) and by the tuning gains. The observer must be initialized with an estimate of KT/J. While moderate errors (for example, 20%) have little effect, large-scale errors will degrade the observed velocity signal significantly. Typically, the magnitude of KT will be known well enough but inertia often is not known well and, in some applications, even varies significantly during operation. The effectiveness of the observer is reduced in applications with large-magnitude variation of load inertia; in such cases a physical acceleration signal such as one provided by a Ferrari sensor may be used. The tuning of the observer is similar to tuning for the RDC.

It should be stated that there are a few differences between the traditional observer and the observer shown in Figure 6b. First, this observer moves the motor torque constant and inertia outside the observer loop to have a structure similar to that of the traditional RDC. The plant is simplified to a simple integrator rather than using, say KTJs, a common motor model. Second, the second integrating term on the bottom path is considered part of the sensor, not the plant. This is done since the state of interest is velocity, not position. This is because the
dynamics of the velocity loop are so much higher than the position loop, that phase lag reduction in the velocity signal is paramount. So, there are some differences between the observer of Figure 6b and the physical system; however, the dynamics of the system are well represented and the velocity signal from the observer is a considerable improvement over the signal from the RDC, as will be demonstrated in the next section.

Advantages of observer-based R/D conversion

The primary advantage of observer-based feedback is the reduction of phase lag in the control loop. Another advantage is the derivation of observed acceleration, which can be used to reduce problems with mechanical resonance. A third advantage is the derivation of observed disturbance torque, which can be used to improve the disturbance response of the drive. In this section, the improvement of phase lag is verified in a lab experiment using Kollmorgen Seidel’s ServoStar 600 amplifier. This amplifier formerly relied solely on software-based traditional (non-observer) RDC [4], but now includes the RDC observer structure.

Figure 7. Improvement in stability from reduction of phase lag from a) a traditional RDC to b) and observer-based RDC.

Reduction in phase lag

As discussed in earlier sections, the phase lag created by RDC can cause instability in a servo system, especially when servo gains are raised to high levels. The step response of such a system is shown in Figure 7a. Here the servo gains are set high enough that the system will respond to a 200 RPM step change in speed in 10 mSec. However, when the gains are set sufficiently high to produce the necessary responsiveness, the stability margins are reduced and substantial ringing is generated.

The observer improves the stability margins considerably, as shown in Figure 7b. Here, the servo gains are the same, but the ringing is removed. For reference, the servo gains, current loop, and RDC compensation gains are identical. The only difference between Figure 7a and 7b is addition of the power converter path to the RDC.

Derivation of observed acceleration feedback

A second advantage of the observer-based RDC is that observed acceleration feedback is provided through the observer structure. This signal can greatly reduce problems with mechanical resonance. This subject is discussed [11] which is also presented at this conference, as well as in [6-10].

Derivation of observed of torque disturbance

A third advantage of the observer-based RDC is that observed torque disturbance is provided by the observer structure. This can be used for disturbance decoupling [12], a technique where the disturbance signal is fed back with a polarity inversion to the power converter input. The use of disturbance decoupling can greatly improve the dynamic stiffness of the servo system.

The disturbance decoupled velocity control loop is shown in Figure 8. The output of the observer compensator is marked as $T_{DO}$ or “observed disturbance.” While a detailed discussion of this topic goes beyond the scope of this paper, readers can see that this signal represents the torque disturbance. Notice that the signal is added into the model system after the power converter output, and compare this to actual torque disturbance, $T_D$, which is added to the actual system in approximately the same position. It should be apparent that, assuming the models for sensor and plant are accurate, the only way for the observer compensator to drive the error to zero is for its output to be equal to the actual torque disturbance. See [9] for more information.
Once the observed torque disturbance signal is available, it can be fed back to the power converter output as shown in Figure 8. So, when a disturbance moves the motor, the observed disturbance signal will provide an estimation of that disturbance, which can be fed to the converter in opposition. Since the observed torque disturbance responds from DC to the observer bandwidth (typically >200 Hz), the response to the disturbance is much more rapid than the response from the velocity loop (typically <100 Hz).

Conclusion

The traditional process of RDC, whether carried out in hardware or software, generates phase lag in servo systems. By restructuring the RDC into an observer, this phase lag can be reduced or even eliminated. The observer uses the power converter output to predict motor movement while the correction path from the sensor ensures that estimation errors do not accumulate. This combination provides a velocity feedback signal that is more representative of actual motor velocity than can be derived from the traditional RDC output. By eliminating phase lag in the velocity feedback signal, the observer allows more responsive servo loops. In addition, the observer provides two other signals: observed motor acceleration and observed torque disturbance. These signals can be employed to further improve servo performance.

References