SERVO**STAR**® S- and CD-Series Position Feedback Resolution and Noise

Position feedback resolution has two effects on servo system applications. The first effect deals with the positioning accuracy of the device itself. A motion system cannot hold position closer than position feedback accuracy. The second effect, noise generation, is more difficult to understand and predict. However, in many highly-responsive systems, the noise limit is more important than the positioning-accuracy limit.

This document focuses on the relationship between noise and position feedback resolution. The amount of noise depends on three factors: the mechanical gain of the system, the responsiveness or bandwidth (BW) of the system, and the filtering of the velocity loop. The mechanical gain depends on the current capacity (I) of the drive, the torque sensitivity of the motor (K_T), and the total inertia of the system (J). It can usually be calculated with accuracy. The filtering can be explicit (low-pass filters) or implicit (current loops). Both responsiveness and filtering must be estimated for most applications. The estimations can come from measurements on the system or derived from the performance required in the application.

This document develops an explanation of resolution noise and provide a means for estimating the amount. The companion Microsoft Excel® file can be used to estimate the noise for a given application.

Theory

Resolution noise comes from the proportional gain (K_V) in a velocity loop. For the purposes of understanding resolution noise, the servo loop will be modeled as a simple proportional controller. The addition of an integral gain in the velocity loop, or in the position loop, has little effect on noise amplitude.

All compensation modes (COMPMODE) of the SERVOSTAR® can be viewed as having a proportional gain that generates noise. Even Standard Pole Placement, which has no explicit proportional gain, has an implicit gain term. Knowing the value of the proportional gain is not necessary because it can be derived using only the performance (or performance requirements) of the application.

Figure 1 shows a general proportional velocity loop:

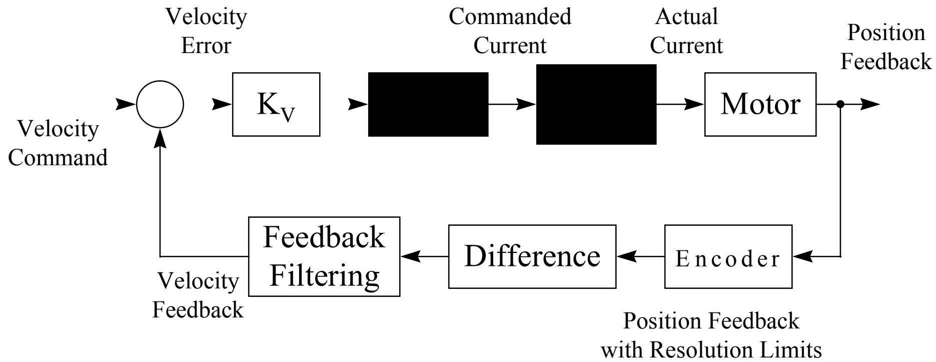

Figure 1: Proportional Velocity Loop

How Gains Generate Noise

The first step to understanding the impact of the loop gains on noise generation is to simplify the general velocity loop of Figure 1 *(see Figure 2)*. The filter blocks are removed and the motor is replaced with a simple K_T/Js^2 model. This model represents a pure inertia with constant torque sensitivity and no friction or viscous damping. The encoder is modeled as an ideal feedback device with a noise source of one least significant bit (LSB).

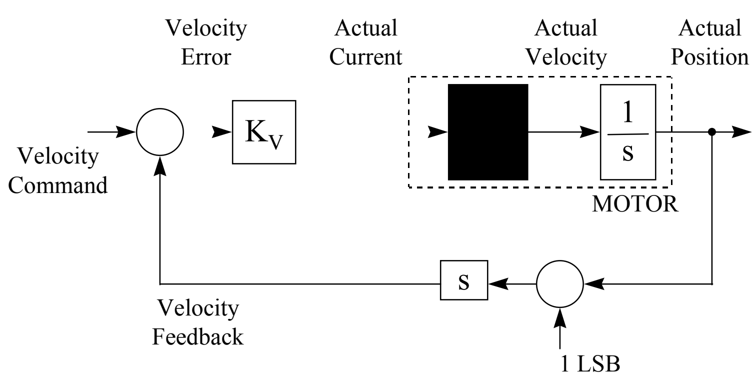

Figure 2: Simplified Proportional Velocity Loop

Applying the *G/(1+GH)* rule to Figure 2, the following equation is developed to estimate the performance of this simplified loop. The response is from velocity command to actual velocity:

$$T(s) = \frac{K_V K_T / Js}{1 + K_V K_T / Js} = \frac{K_V K_T / J}{s + K_V K_T / J} = \frac{\omega}{s + \omega}$$

You may recognize this as a single-pole, low-pass filter with a bandwidth (-3dB frequency) of ω rad/sec or $\omega/2\pi$ Hz. Through substitution, it can be seen that $(K_V K_T)/(2\pi J) = F_{BW}$. Solving for the proportional gain, the following equation is developed: $KV = 2\pi J F_{BW}/K_T$. The gain is now expressed as a combination of known values (K_T, J) making up the mechanical gain of the system and a bandwidth value that can be estimated based on loop performance (F_{BW}). Estimating bandwidth based on settling time is discussed below.

Having established the approximate relationship between K_V and bandwidth, the proportional loop from Figure 1 is redrawn with the filters shown for the SERVO**STAR**®. The difference block will also be redrawn with its z-domain representation: $VN \approx (P_N - P_{N-1})/T$.

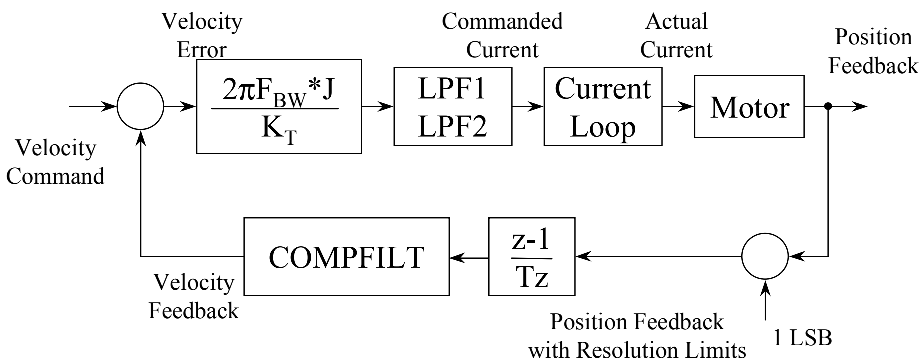

Figure 3: *SERVO**STAR**®* ***Proportional Velocity Loop***

The noise source can now be traced: which is one LSB through the difference (a gain of 1/T), the feedback filter (COMPFILT), the gain K_V, the two optional filters LPF1 and LPF2, and through the current loop. A noise pulse forms a series of two steps, one rising immediately (1/s) and the second falling at the end of one sample $-e^{-sT}/s$. The impact of resolution on noise becomes:

$$Noise(s) = 1LSB \cdot \frac{1}{T} \cdot COMPFILT(s) \cdot \frac{2\pi F_{BW} J}{K_T} \cdot LPF1(s) \cdot LPF2(s) \cdot CurrentLoop(s) \left(\frac{1 - e^{-sT}}{s} \right)$$

Making the Estimations

The noise equation above can be divided into two parts: a pulse of noise and the filtering that reduces it:

$$Pulse(s) = 1LSB \cdot \frac{1}{T} \cdot \frac{2\pi F_{BW} J}{K_T} \cdot \left(\frac{1 - e^{-sT}}{s} \right)$$

$$Filter(s) = COMPFILT(s) \cdot LPF1(s) \cdot LPF2(s) \cdot CurrentLoop(s)$$

Estimating the Noise Pulse

Estimating the noise pulse requires the following information:

- Total inertia (J) for motor and load
- Torque sensitivity (K_T)
- System Bandwidth (F_{BW})
  F_{BW} depends on the application. Typical bandwidths for servo systems range from 25 Hz to 200 Hz. For systems with very large inertias, the bandwidth may be as low as 2 or 3 Hz. One way to estimate bandwidth is to derive it from settling time. If a system is required to settle in T_1 seconds, the bandwidth will be between $1/2T_1$ and $1/T_1$. For example, in a system with a settling time of 10 mSec ($T_1 = .01$), the velocity loop bandwidth would usually have to be between 50 and 100 Hz. This assumes proper system tuning and the use of feed-forward gains. Increasing feed-forward usually allows the system to work with lower bandwidths.
- Resolution in radians. This is 2π/(4*lines) radians for encoders where *lines* is the number of encoder lines per revolution. Resolver resolution is discussed below.
- Sample time (T) is fixed for the SERVO**STAR**® at 0.000250 sec (250µsec).

The amplitude of the noise pulse is then:

$$Pulse_{Amplitude} = \frac{2\pi}{4 \cdot Lines} \cdot \frac{1}{T} \cdot \frac{2\pi\, F_{BW}\, J}{K_T}$$

This represents the worst case noise pulse of current that can be generated by the resolution. This noise pulse can be surprisingly large. For example, if a 1000 line encoder were used with a K_T of 1 N-m/amp, an inertia (J) of 0.002 kg-m^2, and the system required a bandwidth of 100 Hz, each transition of an LSB would cause as much as 7.8 amps of noise. Most of the time however, the impact of filtering substantially reduces the noise peaks.

Estimating the Effect of Filtering

There are three filters that work to reduce the impact of resolution noise:

- **Configurable feedback filter (COMPFILT)**
  The feedback filter is a fixed single-pole low-pass filter with a bandwidth of 440 Hz that can be enabled through the **MOTIONLINK**® velocity loop compensation screens. For most applications, this filter should be used to reduce resolution noise. Normally it has little effect on system performance.
- **Configurable low-pass filters (LPF1/LPF2)**
  LPF1 and LPLF2 are single-pole low-pass filters that can be individually enabled and frequency configured by the user. They should be set to approximately five times the velocity loop bandwidth.

- **Current loop**
  The current loop is an implicit low-pass filter. It is usually modeled as a double-pole filter with a damping ratio of approximately 0.7 and a break frequency of about 900 Hz.

The effect of filters is more difficult to quantify than the noise pulse. However, an Excel spreadsheet that does quantify filtering is available as a companion to this application note. Figure 4 is a sample result from this spreadsheet. It shows noise in amps vs. time in seconds. As seen in the plot, the filtering in this case reduces the noise pulse by an approximate factor of five.

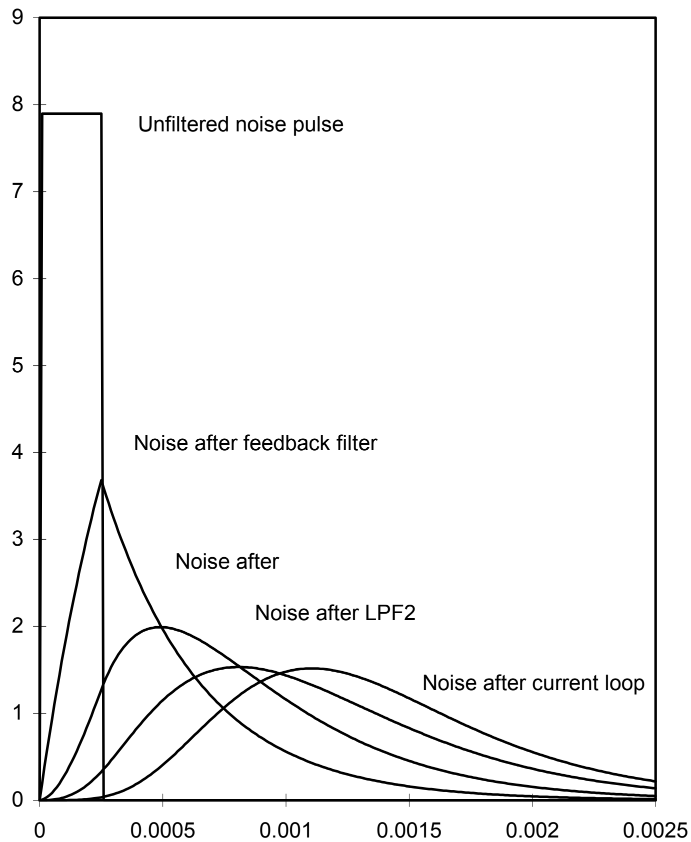

Figure 4: Impact of Filtering on Noise

Combining the Effects

A final estimate requires a measure of how many pulses will occur in a short period of time, because more pulses generate more noise. Figure 4 shows a pulse of noise caused by a single transition of the feedback device. However, in real systems, there may be multiple quick transitions of the feedback device. Estimating this effect is difficult, but a figure of between 1.5 and 3.0 noise pulses has been seen in the laboratory. The accompanying Excel spreadsheet uses these boundaries (shown in red) to estimate noise.

Understanding Resolvers

Resolver noise can be estimated with the same method. Resolver-to-digital conversion is carried out to either 12, 14, or 16 bits depending on the maximum speed of the system. However, Danaher Motion has patented technology that allows interpolation between resolver LSBs. Using this technology, all resolvers have approximately 16 bits of resolution, which is equivalent to 65536 counts or 16384 lines per electrical revolution of the resolver. If the application uses a multi-speed resolver, multiply 16384 by the speed. For example, if the application uses a 3 speed (6 pole) resolver, the equivalent resolution is approximately 16384 * 3 or 49152 lines per mechanical revolution.

Measuring Resolution with the Drive

The SERVO**STAR**® can be used to measure resolution noise. Configure the Record Screen in **MOTIONLINK**® to record ICMD (not the I variable), step the motor, and view the results.

The I variable is a smoothed version of the current. ICMD is a precise recording of the current command that also includes noise pulses and all the filters except the current loop. In most applications however, the current loop is the highest frequency filter and thus has the least impact. In these cases, ICMD and the true current will be very close (as shown in Figure 4).

MOTIONLINK ***presents the current command scaled in 0.1% of peak current. For example, a value of 50 in a 3 amp SERVO****STAR*® ***indicates 5% of peak current (6 amps) or 0.3 amps. The peak current is normally twice the continuous and the drive is rated according to continuous current. To make sure of the peak rating, go into the*** *MOTIONLINK* ***terminal screen and type "DIPEAK." This gives the peak rating in 0.1 amp (e.g. a value of 60 in DIPEAK indicates a 6 amp peak drive)***

Using the Spreadsheet

Use the accompanying spreadsheet (ASU010.xls) to estimate the resolution noise encountered in a given application. The spreadsheet can be obtained from either the Product Support Package (PSP) CD-ROM shipped with the product or from the website (www.DanaherMotion.com). There are nine parameters that must be entered in the spreadsheet:

- **$J_{motor} + J_{load}$**
  Enter the system inertia in either lb-ft-s^2 or k-m^2.
- **K_T**
  Enter the motor torque constant in units that match the inertia above (either lb-ft/amp or N-m/amp, respectively).

- **Bandwidth**
  Enter the approximate velocity loop bandwidth in Hz. If the bandwidth is unknown, but the required settling time (T_1) is known, approximate the bandwidth as being between $0.5/T_1$ to $1/T_1$. Bandwidth should not be larger than 200 Hz.
- **Encoder resolution**
  Enter the encoder lines per revolution. For resolvers, use 16384 * the number of resolver pole-pairs (most SERVO**STAR**® systems have one).
- **Use COMPFILT**
  COMPFILT is a single-pole 400 Hz low-pass filter that can be enabled or disabled. COMPFILT should be used in all but the most responsive systems (e.g. use COMPFILT if the bandwidth is below 100-150 Hz).
- **Use LPF1**
  Turn the filter on/off and set the frequency. LPFHZ1 reduces the available performance of the system; the degradation is small if the filter frequency is high. Usually, LPF1 can be set at five times the bandwidth.
- **Use LPF2**
  Turn the filter on/off and set the frequency. LPFHZ2 reduces the available performance of the system; the degradation is small if the filter frequency is high. Usually, LPF2 can be set at five times the bandwidth.

The accompanying spreadsheet does not analyze servo performance and allows values that would produce an unstable system. For example, the spreadsheet allows a bandwidth setting of 500 Hz and LPF1 and LPF2 Hz as 100 Hz. Such settings would indicate good noise performance, but would cause instability in the servo system. Never use low-pass filters of less than four times the bandwidth.