Using "Jump Error" to Assess the True Performance of Position Encoders

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Traditionally, the performance of position encoders is specified in terms of "Interpolation Error" and what might be called "Gain Error." Gain Error can be largely avoided by calibrating the encoder output and multiplying each reported encoder position by a gain correction factor. Gain Error is usually not specified and instead high precision encoders are supplied with a gain correction constant that can be used by the software or motion controller to correct for Gain Error. Interpolation Error, also called Sub-Divisional Error (SDE), is due to imperfections in the ability of the interpolation electronics (and sometimes the optics and scale) to determine position within the pitch of the scale markings. The popular Sin/Cos interpolation method commonly resolves the scale pitch into as many as 2^{11} parts, while the SPPE method has been shown to resolve the scale pitch accurately into 2^{19} parts.

The unstated assumption behind using Interpolation Error as the primary measure of encoder merit is that all scale markings are accurately placed at a constant pitch, i.e., that random variations in the location of the grating lines is much less than the Interpolation Error. This is contrary to user experience, especially with users desiring high precision position encoders, where random errors have sometimes been found to be many times greater than the interpolation error. Interpolation Error is cyclic, with the period being the grating pitch or a harmonic. Imperfections in the location of the lines of the grating produce a random error, which we are calling short-range Jump Error. In some applications cyclic error is a far bigger concern than random error, and in other applications *any* deviation from intended position is important, and since short-range Jump Error can be many times larger than Interpolation Error it is important to know Jump Error.

There are many potential sources of Jump Error. The most obvious cause is what might be called "Stitching Error," which is part of the manufacturing process of the scale. A scale is usually manufactured by exposing a pattern of lines, and then a neighboring pattern is created by repeating the same process on an adjacent area of the scale. Within each area of exposure there may be small variations in the line spacing. But moving to an adjacent location may involve error that is far greater than the line-to-line error within a pattern. The actual error at the seam will be the sum of random variations within a pattern plus error in moving the pattern to the adjacent location. Jump Error is a property of the encoder scale and is independent from the encoder head.

Nikon constructed the special apparatus shown in figure 1 to measure Jump Error. Two high performance incremental encoder heads are firmly located 15mm apart. The encoder heads are thermally connected to keep them at the same temperature and their design and construction provides minimal change in output due to thermal

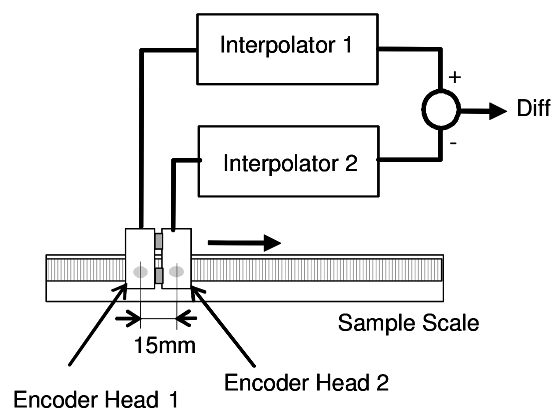

Figure 1 - Apparatus to measure Jump Error

variation. The interpolation electronics are constructed to cause each encoder head to sample the scale position at exactly the same time. The output from the apparatus is the difference between the outputs of the two incremental encoder heads, which will be zero after the encoders are initialized.

Next, Nikon attached the scale to a high quality linear stage, moved the stage at constant velocity, and sampled the encoder heads at 10KHz. The resultant differential position data were then high-pass filtered to remove the spatial frequencies with period longer than 1mm, and Interpolation Error, which is periodic, were removed via digital filtering. The result is short-range Jump Error as shown in figure 2.

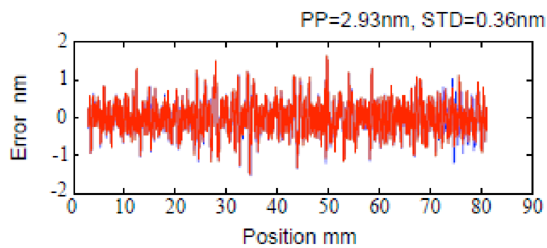

Figure 2 - Jump Error (times two)

The peak-to-peak error shown in figure 2 is 2.93nm, and the measurement apparatus is measuring two times the short-range Jump Error. Thus, the worst case short-range Jump Error for this scale is ±(2.93/4) or ±0.73nm. Nikon scales manufactured by this process are listed as having short-range Jump Error within ±1nm (typical). Nikon also offers scales made using different manufacturing processes. Some additional types of scales have the same Jump Error, and others have typical Jump Error as large as ±10nm, which is still exceptionally high performance for most encoder applications.

The plot shown in figure 2 actually represents the superposition of six measurements at each position location, allowing one to calculate the repeatability of the measurements. The repeatability of each measurement was 88pm (1σ), indicating that the measurement apparatus was extremely repeatable and that repeatability errors due to the measurement apparatus are insignificant compared to short-range Jump Error.

To properly determine the worst case error reported by an encoder, one would add the worst case Interpolation Error, the worst case short-range Jump Error and any other potential error sources, such as Gain Error, error due to temperature variation, and long-range non-linearity (if it is not eliminated by mapping). While doing this is mathematically correct to determine the worst case error, in many cases it is unnecessary for two reasons. First, if one source of error, such as the Jump Error (which is not commonly specified by most other manufacturers of position encoders) dominates, then you can ignore the other error sources. Second, if the sources of error are independent, which they are, a proper statistical treatment would be to compute the standard deviation of each error source, calculate the square root of the sum of the squares to determine the standard deviation of total error (σ_T), and then estimate the worst case error as $3\sigma_T$. Of course the repeatability of the encoder measurements should be far better than any of the errors, but to make sure it is included, one might include the repeatability of the encoder measurement as one of the error sources