HEIDENHAIN

Technical Information

Rotary Encoders on Servo Motors for Linear Axes: Influence on the Surface Quality of Milled Workpieces

In many areas of the machine tool industry, particularly in mold making, workpieces with tight tolerances and flawless surfaces are the goal. To achieve this aim in the shortest possible time is an extraordinary challenge. Mold making demands large cutting volumes during roughing, followed by high surface quality in the subsequent finishing process (Figure 1). Only if the quality of the milled surfaces is high is it possible to avoid subsequent cost due to manual polishing for example.

In addition to the machine mechanics, the control and the tools used, the applied axis measuring technology is decisive for a high-value milling result. Particularly in a wavelength range between 0.5 mm and 5 mm, periodically repeating surface defects on the workpiece surface are visible to the human eye and therefore bothersome—especially in mold making. Interpolation errors of the axis encoders, among other causes, can be responsible for these errors. Besides high-end linear encoders, rotary encoders with especially small interpolation error in the linear feed axes are crucial in order to attain the required high workpiece surface quality.

Figure 1: Mold making workpiece during milling

December 2015

Causes of visible surface defects

Interpolation error and its effects

Surface defects stand out
The human eye is very sensitive to structural changes or even the smallest defects on a surface. A single pixel error on the monitor, for example, with a display comprising up to five million pixels, is immediately visible. The human eye is even more sensitive to periodic surface faults.

Particularly in mold making, periodic surface defects are disturbing and require expensive rework. Surface defects are visible on part surfaces as shadows or fluctuations in contrast. These can be attributed to various causes, e.g.:

- vibrations in the machine that disturb the machining process (see [1]),
- interpolation error of the axis encoders used (see [2])

Signal deviations cause interpolation error
The axis encoders generally built into today's machine tools establish the position value of a feed axis principally from two components:

- an absolute part, which after switch-on ascertains the feed-axis position with limited accuracy,
- an incremental part, which provides two sine waves (A and B) with a 90° phase shift

To attain the required resolution, the periodic analog signals A and B are subdivided further with interpolation methods. The interpolation processes operate without error as long as the two sinusoidal output signals are ideal and are electrically phase-shifted to each other by exactly 90°. Deviations generate errors that repeat themselves with each period of the scanning signals (signal period). This is therefore referred to as interpolation error (Figure 2).

There are many factors critical for the size of the interpolation error, such as:

- the size of the signal period,
- the homogeneity and period definition of the graduation,
- the quality of scanning filter structures,
- the characteristics of the sensors, and
- the stability and dynamics of further processing of the analog signals

Effects of interpolation error
The mold making industry is demanding workpieces with increasingly complex geometries. In five-axis machining, all combinations of axis movements are common. If an inclined or curved machining surface is manufactured through the interpolation of multiple NC axes, the interpolation error can be seen directly on the workpiece.

This becomes particularly apparent when an inclined surface with a small angle is machined. The interpolation error of an encoder (e.g. in Z direction) can be made visible by projection on the inclined workpiece surface (Figure 3). Because of the inclination, an n-fold stretching of the signal period appears in the tool path. While the axis in Z direction moves by only one signal period, the X axis moves n times more. A wave appears on the inclined workpiece surface with a wavelength that corresponds to the n-fold signal period of the Z-axis encoder. A wavelength of 0.5 mm to 5 mm is especially easy for the human eye to detect.

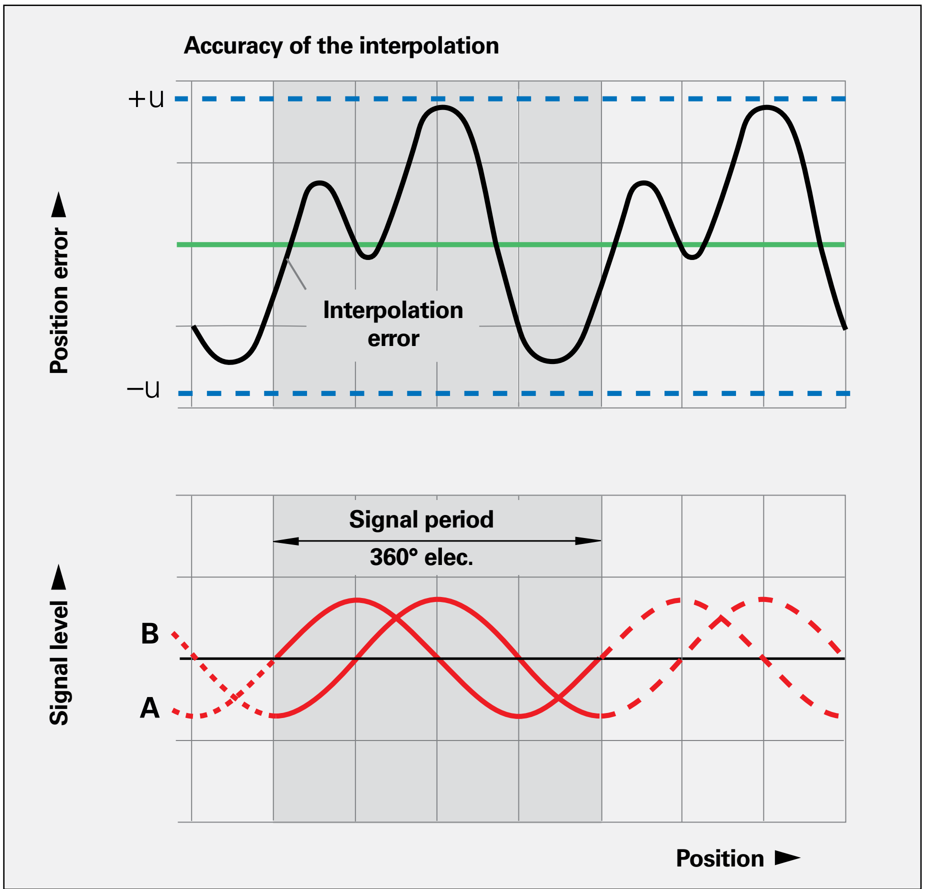


Figure 2: Position errors within one signal period (interpolation error)

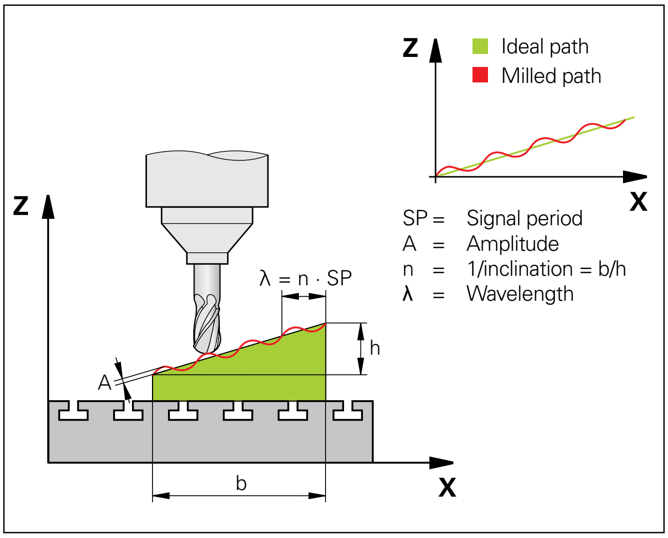


Figure 3: Illustration of interpolation error on a workpiece incline

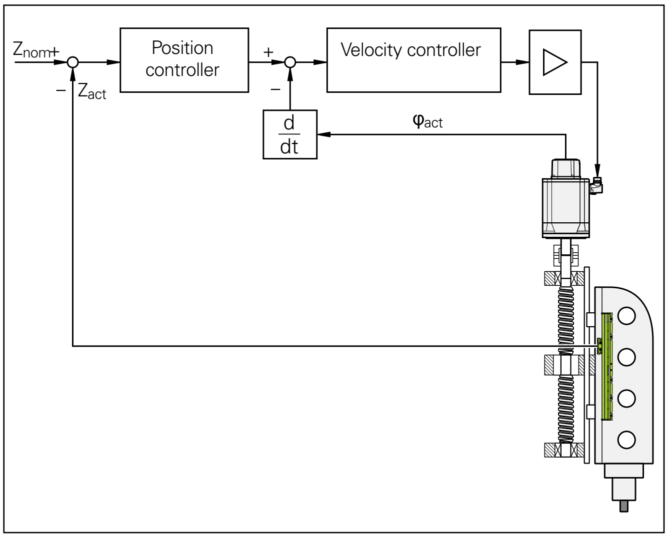


Figure 4: Schematic representation of a feed axis

Position and velocity measurement in feed axes
Figure 4 shows the basic design of a servo-controlled feed axis with servo motor, recirculating ball screw, spindle axis structure and axis measuring technology. The position of the spindle axis is measured with a linear encoder and returned to the position control loop of the axis as an actual position value. A rotary encoder as a second measured value encoder is located on the servo motor of the feed axis for measuring the motor shaft angle. The signal from this rotary encoder is used to determine the actual speed.

Source 2 shows results from machining tests in which the interpolation errors of linear encoders in magnitudes of ±200 nm become visible as surface defects on the workpiece. The HEIDENHAIN LC 100 linear encoder used for the comparison, with an interpolation error of significantly less than ±100 nm, caused no visible surface waves.

The machine tool used in the tests outlined below uses HEIDENHAIN type LC 483 linear encoders in all linear axes. These also have an interpolation error of distinctly less than ±100 nm, indicating that no visible surface waves may be expected. This principle is the basis for the following observation and description of the influence of rotary encoder interpolation error on the surface defects of milled workpiece planes.

The interpolation error of a rotary encoder corresponds to a short range angle error within a signal period. To achieve the desired levels of accuracy for workpiece geometries and surfaces, machine tools with high geometric accuracy are normally used. With a mechanically stiff and backlash-free feed axis, the interpolation error of the rotary encoder is converted via the kinematics of the ball screw into a linear error. This means that from a specific rotary encoder interpolation error size and under further conditions as specified below, surface defects on the workpiece are to be expected.

An increasing travel speed of the encoder head over the scale with a periodically recurring error will lead to an increase in frequency. Therefore, the interpolation error frequency depends on the feed rate. Because of the differing cutoff frequencies (bandwidth) of the position control loop and speed control loop, the interpolation error of the encoder becomes noticeable to varying degrees on the tool center point depending on the feed rate. With low feed rates (low interpolation error frequency), the interpolation error of the rotary encoder is corrected by the position controller. If the frequency of the rotary encoder interpolation error exceeds the cutoff frequency of the position control loop (higher feed rate), no more adjustment takes place. Increased occurrences of this interpolation error at the tool center point can then be expected.

Factors influencing the interpolation error

Feed rate and bandwidth of the position and speed controller

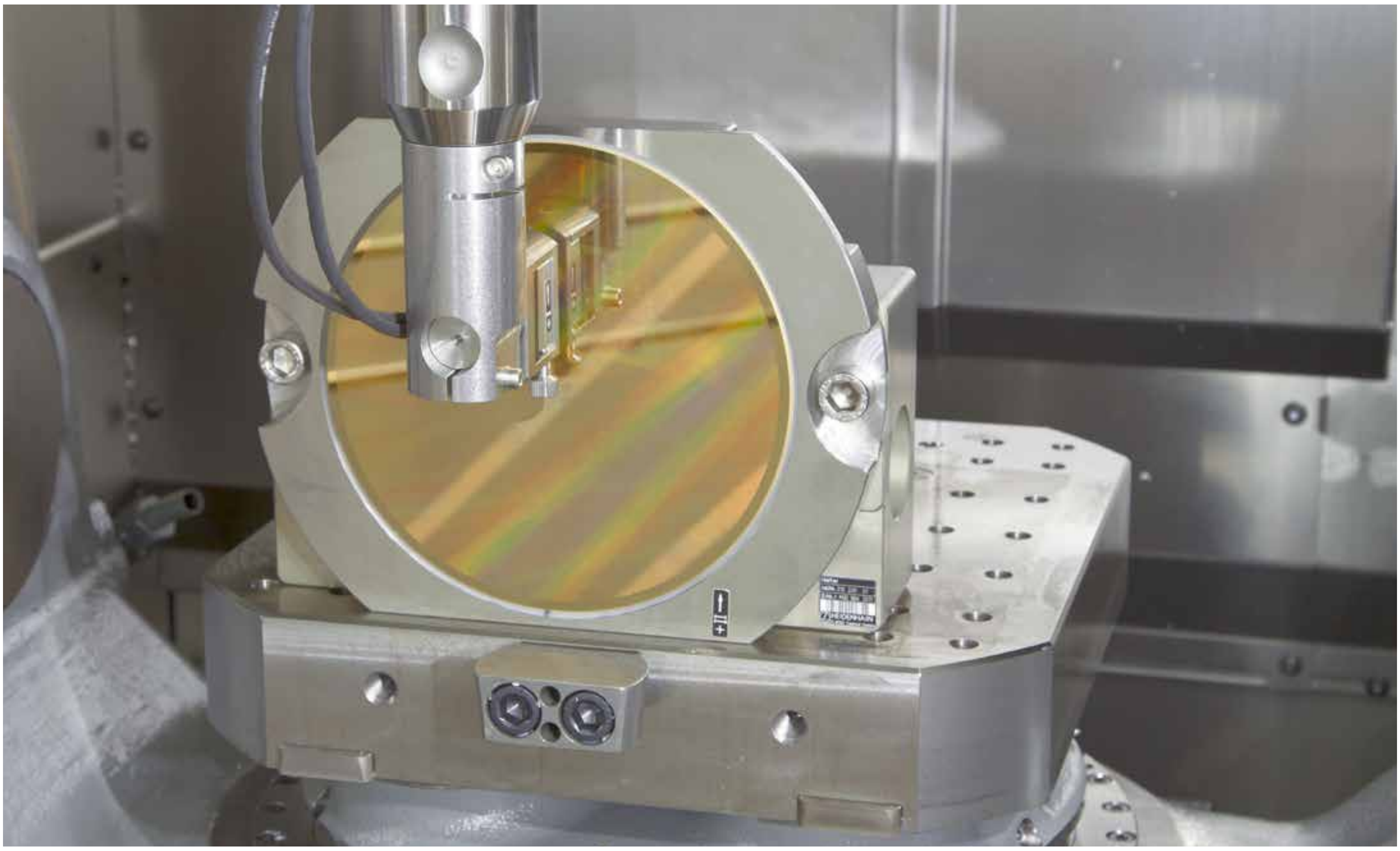


Figure 5: Measuring test setup with KGM 181 grid encoder

Test setup with grid encoder
In order to be able to separate the effects of the machining process and the movement of the tool center point, a HEIDENHAIN KGM 181 grid encoder is used to determine the contouring deviations prior to machining. The grid encoder permits non-contacting determination of the contouring deviations between the tool center point and machine table in the plane of the two moving feed axes. Figure 5 shows the test setup. The tests were conducted with a high-end die and mold machine.

The measuring plane is formed via the X axis and Z axis of the machine. The servo motor of the Z axis is coupled directly to the recirculating ball screw spindle, so that no further transmission lines in the drive train exist apart from the ball screw. The pitch of the ball screw is P = 20 mm.

The Z axis of the machine is relevant for the observations. The rotary encoder of the servo motor is varied on the Z axis for the tests. Two high-end, mounting-compatible rotary encoders are used, each with 2048 graduations on the circular scale. Rotary encoder 1 has an interpolation error 3 times higher than that of rotary encoder 2.

As described above, the interpolation error of the rotary encoder are converted via the circulating ball screw drive into linear error. The signal period of the linear movement is calculated via the ball screw pitch and the line count of the encoder:

$$SP_{RElin} = \frac{P}{LC} = \frac{20\text{ mm}}{2048} \approx 9.8\text{ µm} \quad \text{(Equation 1)}$$

For the workpieces to be machined, a traverse path of b = 60 mm and h = 0.4 mm is defined for the grid measurement. These parameters result from the equation specified in Figure 3 on page 3 for calculating the wavelength under consideration of SP_{RElin} and the sensitivity of the human eye for periodic form errors with λ = 0.5 mm to 5 mm.

Thus, with excessive interpolation error, a signal period of 9.8 µm causes a contouring deviation of λ ≈ 1.5 mm.

Measuring results confirm interrelations
Figure 6 shows the measuring results using rotary encoder 1 and two different contour speeds. The lower speed (500 mm/min) is generally for machining steel workpieces with small cutter diameters (e.g. Ø 6 mm), and the higher speed of 4000 mm/min for machining aluminum.

The motion error traces show that at a feed rate of 4000 mm/min, wave-shaped contouring deviations occur in the Z direction. By zooming the view, a wavelength of about 1.5 mm becomes visible. This corresponds to the expected wavelength based on the interpolation error of the rotary encoder on the servo motor of the Z axis.

Figure 6: Measuring results for rotary encoder 1 with a 3-fold higher interpolation error

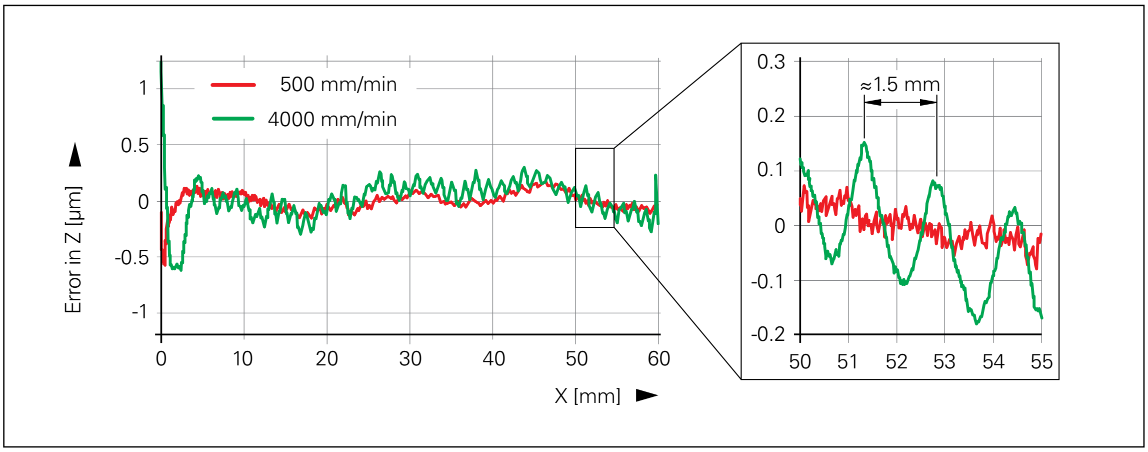
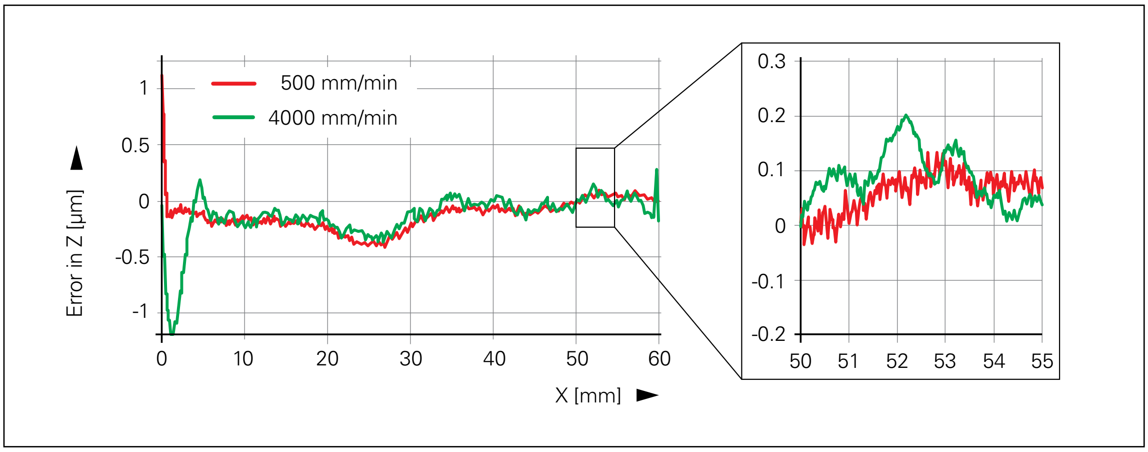


Figure 7: Measuring results with rotary encoder 2



As described above, the interpolation error frequency depends on the feed rate. Whether the interpolation error of the rotary encoder occurs as a contouring deviation on the tool center point or is adjusted continues to depend on the bandwidth of the position and speed controller. Equation 2 (calculation of Z axis speed) and Equation 3 are used to determine the frequency of the interpolation error in the rotary encoder signal and the frequency with which it is returned to the speed control loop of the Z axis:

$$v_Z = \sqrt{\frac{v_B^2}{1+\left(\frac{b}{h}\right)^2}} = \sqrt{\frac{4000^2}{1+\left(\frac{60}{0.4}\right)^2}}\left[\frac{mm}{min}\right]$$

$$= 26.7\,\frac{mm}{min} \qquad \text{(Equation 2)}$$

$$f_{SP} = \frac{v_Z}{SP_{RElin}} = \frac{26.7\ mm/min}{9.8\ \mu m}$$

$$\approx 45\ Hz \qquad \text{(Equation 3)}$$

At a feed rate of 4000 mm/min with the existing inclined plane, the interpolation error is manifested with a frequency of approx. 45 Hz in the rotary encoder signal. The feedback and differentiation of the rotary encoder signal (Figure 4, page 3) does not influence the frequency of the encoder interpolation error and therefore also exists in the actual speed signal.

The speed controller with a bandwidth of greater than 80 Hz follows the oscillation of the rotary encoder interpolation error. The feed movement implemented on the Z axis structure now has oscillation corresponding to the frequency of the interpolation error. In the present case, the rotary encoder interpolation error frequency of 45 Hz exceeds the cutoff frequency of the position control loop (f_{l_PC} < 40 Hz). If the amplitude of the interpolation error is now high enough, a corresponding contouring deviation on the tool center point is noticed (cf. the measuring results with rotary encoder 1).

Figure 7 shows the measuring results for rotary encoder 2 mounted on the servo motor of the Z axis with otherwise identical conditions. Due to the 3-fold lower interpolation error with rotary encoder 2, superimposed waves no longer occur in the curves of the low or high feed rates. The interpolation error of the rotary encoder on the servo motor of the Z axis is now so small that no detectable periodic contouring deviations are caused between the tool center point and the machine table. The following milled workpieces show that this also applies for the relative movements between the tool and workpiece, i.e. the machined surface.

Low interpolation error avoids contouring deviations
Surface quality starts with the rotary encoder

Workpiece machining
To show the influence of the interpolation error on the machined surface quality, the previously specified inclined plane with b = 60 mm and h = 0.4 mm is machined on a workpiece with use of rotary encoder 1 or rotary encoder 2. The workpiece undergoes multipass milling in the Y direction with a downward cut to produce this incline. The line spacing in the Y direction and finishing allowance each consist of 0.1 mm. Figure 8 shows the machining situation in the machine tool with the set technology parameters.

Figure 9 shows the milled surfaces. The surface with use of rotary encoder 1 is shown in the top image. The wave forms with $\lambda \approx 1.5$ mm caused by the interpolation error of this encoder create an objectionable shadowing effect despite the low amplitude of only around 0.1 µm. This means that the contouring deviations determined previously with the grid encoder measurements lead to an obviously inferior surface quality on the workpiece.

Technological parameters	
Tool diameter in mm	6
Number of teeth	2
Spindle speed in rpm	18000
Feed rate in mm/min	4000
Cutting material	PCD
Workpiece material	Aluminum

Figure 8: Machining situation and technological parameters

The change to rotary encoder 2 on the servo motor of the Z axis with a 3-fold lower interpolation error—with otherwise identical conditions—results in a significant improvement of surface quality (Figure 9, below). Thanks to the lower interpolation error of the rotary encoder, the previously existing regular surface waves are no longer visible. The HEIDENHAIN ERN 1387 rotary encoder has an even lower interpolation error than rotary encoder 2. The unit is used among other applications for the speed control of electrical drives.

Conclusion
Axis encoders with low interpolation error are needed to produce high quality surfaces. Because the interpolation errors are manifested as contouring deviations between the tool and workpiece with different feed rates, this not only concerns the linear encoders of the feed axes but also the encoders on the servo motors. To avoid the contouring deviations outlined above, high quality axis encoders with low interpolation error are needed throughout in the feed axes of a machine tool.

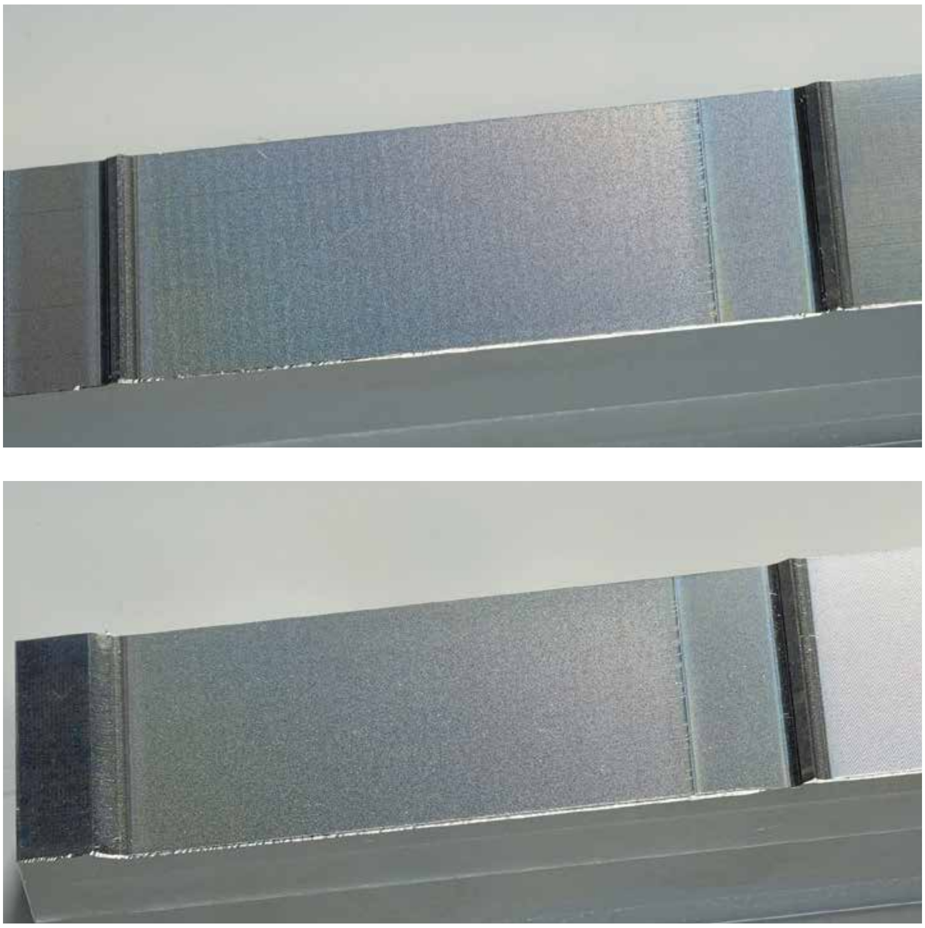


Figure 9: Milled surfaces: Rotary encoder 1 (above) with 3-fold greater interpolation error than rotary encoder 2 (below)

Rotary encoders with very small interpolation error

ERN 1387
Incremental rotary encoders with integral bearing and mounted stator coupling

	Incremental ERN 1387
Interface	∼ 1 V_{PP}[1]
Line count/System accuracy	2048/±20"
Reference mark	One
Output frequency Cutoff frequency –3 dB	– ≥ 210 kHz
Commutation signals	∼ 1 V_{PP}[1]
Width	Z1 track[2]
Voltage supply	DC 5 V ±0.25 V
Shaft	Tapered shaft ∅ 9.25 mm; taper 1:10
Mechanically permissible speed n	≤ 15000 rpm
Starting torque	≤ 0.01 Nm (at 20 °C)
Moment of inertia of rotor	$2.6 \cdot 10^{-6}$ kgm^2
Natural frequency of the stator coupling	≥ 1800 Hz
Permissible axial motion of measured shaft	±0.5 mm
Vibration 55 Hz to 2000 Hz **Shock** 6 ms	≤ 300 m/s^2 [3] (EN 60068-2-6) ≤ 2000 m/s^2 (EN 60068-2-27)
Max. operating temperature	120 °C
Protection EN 60529	IP40 when mounted

1) Restricted tolerances
Signal amplitude: 0.8 V_{PP} to 1.2 V_{PP}
Asymmetry: 0.05
Amplitude ratio: 0.9 to 1.1
Phase angle: 90° ±5° elec.
Signal-to-noise ratio E, F: 100 mV

2) One sine and one cosine signal per revolution; see the brochure *Interfaces of HEIDENHAIN Encoders*

3) As per standard for room temperature;
applies for operating temperature Up to 100 °C: ≤ 300 m/s^2
Up to 120 °C: ≤ 150 m/s^2

HEIDENHAIN

DR. JOHANNES HEIDENHAIN GmbH
Dr.-Johannes-Heidenhain-Straße 5
83301 Traunreut, Germany
☏ +49 8669 31-0
FAX +49 8669 32-5061
E-mail: info@heidenhain.de

www.heidenhain.de

More information:
[1] Technical Information: *Dynamic Precision*
[2] Technical Information: *Perfect Surfaces with HEIDENHAIN Encoders*

1157576-20 · 4 · 12/2015 · F&W · Printed in Germany