# IMPROVING THE CONTOURING ACCURACY OF HIGH SPEED CUTTING CNC LINEAR MOTOR MILLING MACHINE TOOL

**Zoran PANDILOV**[1]

[1] *Institute of Production Engineering and Management, Faculty of Mechanical Engineering,*
*Ss. Cyril and Methodius University in Skopje, P.O. Box 464, MK-1000, Skopje, Republic of Macedonia*
*E-mail: zoran.pandilov@mf.ukim.edu.mk*

***ABSTRACT**: In recent years, instrumentation circular profile tests have been specified to assess the contouring accuracy of CNC machine tools. Such an instrumentation type test is the HEIDENHAIN grid encoder system, which is particularly appropriate for dynamic measurements, especially at high feed rates. In this paper influence of the position loop gain and sampling period on the contouring accuracy of CNC High Speed Cutting linear motor milling machine are effectively studied.*

***KEYWORDS**: Contouring accuracy, CNC linear motor milling machine, High Speed Cutting, position loop gain, sampling period*

## 1 INTRODUCTION

The contouring performance of any CNC machine tool can be established by assessing its ability to move along a specified profile by the simultaneous movement of two or more axes.

When CNC machine tools are used for contouring applications, especially where high feed rates are used, significant dynamic errors can be introduced by the characteristics of the CNC controller and servo feed drive system (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; López de Lacalle & Lamikiz, 2009; Soucek, 2004). The assessment of such dynamic error in CNC machines has traditionally been undertaken by machining a standard circular test piece. Such a test piece is outlined in some of the machine tool standards (ANSI/ASME B5.54, 2020; ISO 10791-7, 2020; VDI/NCG 5211, 2013; JIS B 6201, 2012; British BS 4656-30, 1992; etc.) where the circular profile is produced by simultaneous motion of two linear axes.

An alternative approach to the machining test is an emulation of the circle test by instrumentation techniques. This alternative approach is covered by (ISO 230-4, 2022) standard.

Although instrumentation techniques generally check the machine in no-load condition, they offer certain advantages over measurements under cutting conditions. In particular, tools and test specimens are not consumed and the time consumed in measuring and control of the test piece after machining is eliminated.

The other advantage of these instrumentation techniques is the separation of technological influences from machine influences and capability of distinguishing individual factors of influence.

## 2 HEIDENHAIN GRID ENCODER SYSTEM

In recent years, an instrumentation circular profile test has been specified to assess the contouring accuracy of CNC machine tools. Such an instrumentation type test is the HEIDENHAIN grid encoder system, which is particularly appropriate for dynamic measurements, especially at high feed rates. The grid encoder system is shown schematically in Figure 1. It is primarily designed for performing circular interpolation tests with small radii and curved path tests in order to inspect dynamic performances of the control and the machine and their influence on the contouring accuracy. This is very important especially at high feed rates.

The HEIDENHAIN grid encoder system can perform circular tests with radii from 1 [µm] to 115 [mm] and feed rates up to 80 [m/min] (HEIDENHAIN, 2021). The system consists of a grid plate with a waffle-type graduation, which is embedded in a mounting base, and a scanning head (Figure 1).

During measurements the scanning head moves over the grid plate without making mechanical contact (contact free measurement). Errors resulting from the machine’s geometry have no influence because of the small circular interpolation radius.

For set up, the mounting base is fixed onto the workpiece holding element and aligned. The scanning head is mounted in the locked tool-holding element and is approximately aligned. A spacer foil is used to set the scanning gap of 0.5 ± 0.05 [mm]. A finer setting is made by a set of screws on the scanning head.

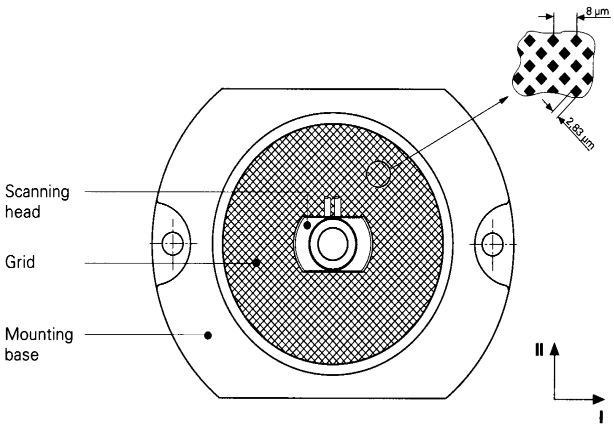

**Fig. 1. HEIDENHAIN grid encoder system (HEIDENHAIN, 2021)**

The HEIDENHAIN grid encoder system measures the actual path. Signals from the scanning head with a signal period of 4 [µm] are sent to PC for further processing using a special counter card which subdivides the measuring signals 1024-fold to provide measuring steps down to approximately 4 [nm] in each axis. The HEIDENHAIN evaluation program ACCOM determines deviations from the ideal circular path and shows them as a motion error trace on the PC monitor. It also calculates numerical values such as circular deviation G, radial deviation F and circular hysteresis H according to (ISO 230-4, 2022) standard,

## 3 THE INFLUENCE OF POSITION LOOP GAIN AND SAMPLING PERIOD ON OPTIMISATION THE CONTOURING ACCURACY OF HIGH SPEED CUTTING CNC LINEAR MOTOR MILLING MACHINE TOOL

One of the most important factors which influences the dynamical behaviour of the feed drives for CNC machine tools is the position loop gain or Kv-factor (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; López de Lacalle & Lamikiz, 2009; Soucek, 2004). The tracking or following error depends on the magnitude of the Kv-factor (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; Lyu et all, 2020; Zhen-Yuan Jia et all. 2018; Liu et all., 2018; Pandilov et all., 2015)

In multi-axis contouring the following errors along different axes may cause form deviations of the machined contours. Generally, position loop gain Kv should be higher for faster system response and higher accuracy.

But, the maximum allowable gains are limited due to undesirably oscillatory responses at high gains and low damping factor which produce significant transient errors and accuracy started do decrease again. That is the reason why optimal position loop gain should be set up experimentally, or calculated approximately.

Experimental contouring measurements with a HEIDENHAIN grid encoder system have been undertaken on a High Speed Cutting CNC linear motor milling machine with SINUMERIK 840 D controller, in order to illustrate a methodology which could be generally applied to any CNC machine. Only two sets of axes have been considered (X and Y). The same procedure can be repeated for other axes.

In all tests the radius of the circle was R=10 [mm], feed rate was constant v=5 [m/min], acceleration was a=10 [m/s2], sampling time was T=0.001 [s] and velocity feed forward was active. The position loop gain Kv in the controller was changed in the range of 5 [(m/min)/mm] to 12.5 [(m/min)/mm]. The tests were done in two directions: clockwise (CW) and counter-clockwise (CCW). The results of the tests, measured values of circular deviation G and radial deviation F according (ISO 230-4, 2022) standard, are given in Table 1.

Circular deviation G is the minimal radial separation of two concentric circles enveloping the actual path (minimum zone circles) and which may be evaluated as the maximum radial range around least square circle. Circular deviation includes only the deviation of form.

Radial deviation F is the deviation between the actual path and the nominal path, where the centre of the nominal path is obtained either from the centring of the measuring instruments on the machine tool or from the least squares centring analysis for a full circle only.

**Table 1. Influence of the position loop gain Kv on circular deviation G and radial deviation F**

| **Kv [(m/min)/mm]** | **5.0** | **7.5** | **10.0** | **12.5** |
|---|---|---|---|---|
| G [µm] (CCW) | 3.4 | 3.3 | 3.2 | 8.5 |
| G [µm] (CW) | 3.4 | 3.2 | 3.1 | 9.1 |
| Fmin [µm] (CCW) | -35.9 | 15.9 | -5.8 | -6.4 |
| Fmin [µm] (CW) | -36.0 | -16.0 | -6.0 | -6.1 |
| Fmax [µm] (CCW) | -30.9 | -5.2 | -2.7 | 2.7 |
| Fmax [µm] (CW) | -29.9 | -4.8 | -2.4 | 3.1 |

The optimal experimental value for the Kv factor is 10 [(m/min)/mm], because it gives minimal values of circular deviation G, minimal radial deviation Fmin and maximal radial deviation Fmax.

We can see that increasing position loop gain Kv in the range of 5 [m/min/mm] to 10 [m/min/mm] decrease G, Fmin and Fmax. It is also obvious that for Kv greater than 10 [m/min/mm] the values of G, Fmin and Fmax started to increase. This can be explained by the fact that transient errors become dominant.

Figure 2 and Figure 3 show graphically some results of the experiments.

Analytical equations (1) and (2) for estimating position loop gain for the classical structure (rotary motor-nut ball screw drive) are given in (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; Soucek, 2004; Pandilov et all., 2015; Pandilov and Dukovski, 2010).

$$K_v = \frac{0.6}{4D^2 \cdot \left(\frac{2D_e}{\omega_e} + \frac{2D_m}{\omega_m} + \frac{T}{2}\right)} \quad [1/s] \tag{1}$$

$$K_v = \frac{0.6}{4D^2 \cdot \left(\frac{2D_e}{\omega_e} + \frac{2D_m}{\omega_m} + \frac{T}{2}\right)} \cdot \frac{60}{1000} \quad [(m/min)/mm] \tag{2}$$

Equations (1) and (2) are function of the following parameters: D-position loop damping, $\omega_e$-nominal angular frequency of the feed drive electrical parts [1/s], $D_e$-damping of the feed drive electrical parts, $\omega_m$-nominal angular frequency of the mechanical transmission elements [1/s], $D_m$-damping of the mechanical transmission elements and T-sampling period [s].

As a result of the absence of mechanical transmission elements for the linear motor feed drive system, equations (1) and (2) are transformed in equations (3) and (4) (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; Pandilov & Dukovski, 2012, Wang 2004, Weck et all. 2001; Gao, 1999).

$$K_v = \frac{0.6}{4D^2 \cdot \left(\frac{2D_e}{\omega_e} + \frac{T}{2}\right)} \quad [1/s] \tag{3}$$

$$K_v = \frac{0.6}{4D^2 \cdot \left(\frac{2D_e}{\omega_e} + \frac{T}{2}\right)} \cdot \frac{60}{1000} \quad [(m/min)/mm] \tag{4}$$

A position loop damping of D=0.707 is preferable according (Brecher & Weck, 2021; Gross et all., 2006; Altintas et all., 2011; Zirn, 2008; Soucek, 2004; Lyu et all, 2020; Zhen-Yuan Jia et all. 2018; Pandilov et all., 2015; Pandilov & Dukovski, 2012, 2010). That is the value, which gives minimal contouring errors. The other numerical values for the parameters of the examined High Speed Cutting CNC linear motor milling machine are: $\omega_e$=942 [1/s], $D_e$=0.55 and T=0.001 [s].

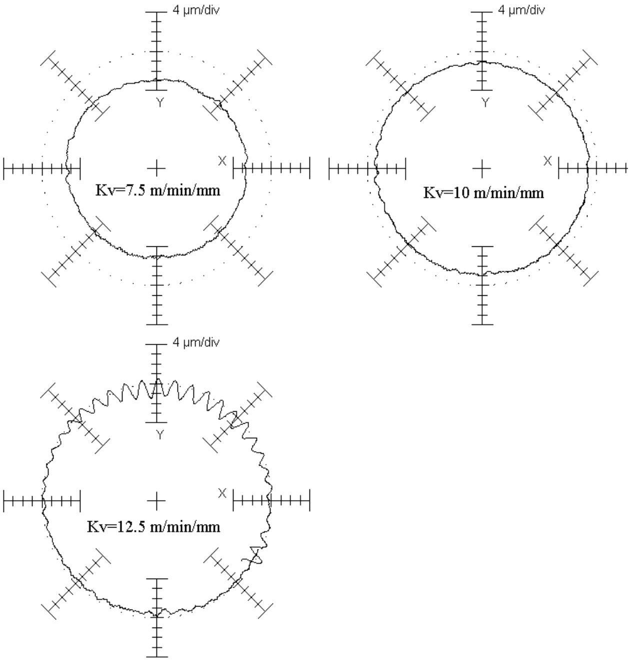

**Fig. 2. Circular deviation G and radial deviation F of the measured circular tests with different position loop gains Kv (R=10 [mm], v=5 [m/min], a=10 [m/s$^2$], T=0.001 [s], CCW, velocity feed-forward active)**

**(......) nominal contour, (-----) actual contour**

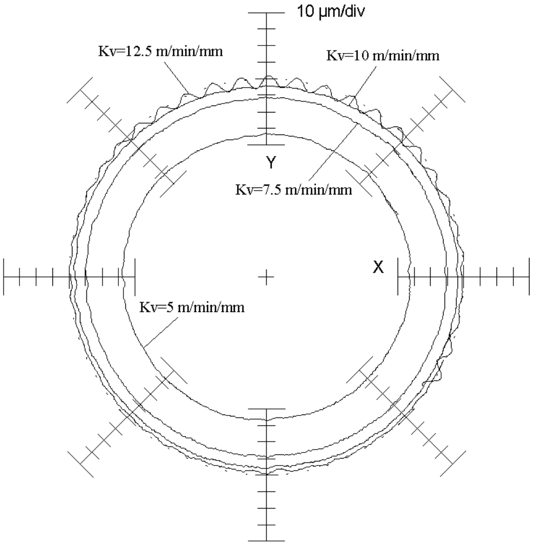

**Fig. 3. A summary polar diagram of circular deviation G and radial deviation F of the measured circular tests with different position loop gains Kv(R=10 [mm], v=5 [m/min], a=10 [m/s$^2$], T=0.001 [s], CCW, velocity feed-forward active)**

**(......) nominal contour, (-----) actual contour**

With the substitution in equation (4) the necessary parameters, the position loop gain value Kv=10.79 [(m/min)/mm] is calculated. The difference between analytically calculated and experimentally obtained value of the Kv-factor is around 7.3%, which is completely acceptable for practical application.

Another parameter, which influences the contouring accuracy, is the sampling time of the controller T. Experiments with changing the sampling period of the controller T were performed.

During the measurements the values of the following parameters: R=10 [mm], v=5 [m/min], a=10 [m/s$^2$] and Kv=10 [(m/min)/mm] were held constant and velocity feed forward was active.

The measurements were done in two directions clockwise (CW) and counter-clockwise (CCW). The results of the experiments are given in Table 2.

**Table 2. Influence of the sampling period T on circular deviation G and radial deviation F**

| **T [ms]** | **1.0** | **2.0** | **4.0** |
|---|---|---|---|
| G [µm] (CCW) | 3.2 | 4.3 | 6.3 |
| G [µm] (CW) | 3.9 | 4.7 | 5.8 |
| Fmin [µm] (CCW) | -5.7 | 2.5 | 3.1 |
| Fmin [µm] (CW) | -6.0 | -3.0 | 3.2 |
| Fmax [µm] (CCW) | -2.6 | 1.4 | 9.0 |
| Fmax [µm] (CW) | -2.3 | 1.7 | 8.7 |

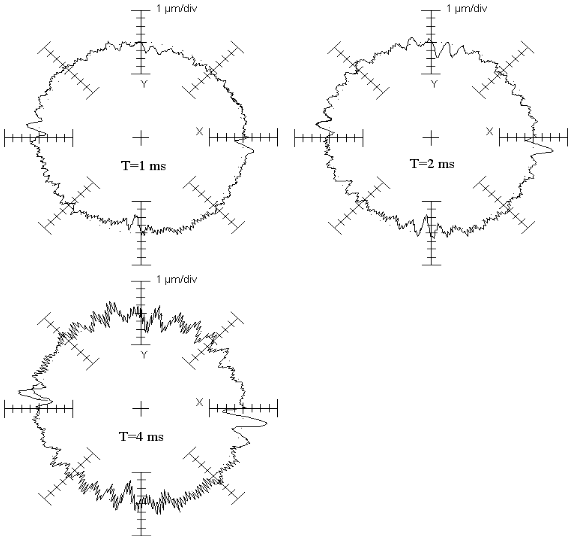

**Fig. 4. Circular deviation G and radial deviation F of the measured circular tests with different sampling periods T**

**(R=10 [mm], v=5 [m/min], a=10 [m/s$^2$],**

**Kv=10 [(m/min)/mm], CW, velocity feed-forward active)**

**(......) nominal contour, (-----) actual contour**

It is obvious that with increasing the sampling period T the values of circular deviation G, minimal radial deviation Fmin and maximal radial deviation Fmax rise up. That is the reason, why the sampling period should be as small as possible

Figure 4 shows graphically some experimental results.

## 4 CONCLUSION

This work has shown that the contouring error at high-speed CNC machine tools can be minimised by appropriate selection of position loop gain Kv in the controller. Criteria used in establishing the optimum Kv value was minimisation of the circular deviation G and radial deviation F.

The test methodology with HEIDENHAIN grid encoder system, demonstrated on the High Speed Cutting CNC linear motor machine with SINUMERIK 840 D controller, offers a general approach for experimental determination of a position loop gain. It was shown too, that the best results in contouring accuracy are obtained with smaller sampling period of the controller.

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