

# OPEN LOOP INERTIAL CROSS-TALK COMPENSATION BASED ON MEASUREMENT DATA

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## ABSTRACT

Inertial cross-talk consists of displacements perpendicular to the intended direction of motion owing to a lateral offset between the driving force and the centre of mass, which causes a tilting motion during acceleration and deceleration. The amount of cross-talk can be determined with a small number of measurements. With the derived proportional factors between acceleration and lateral cross-talk an efficient model can be built and used for offline compensation on an industrial numerical control (NC).

## INTRODUCTION

Dynamic deviations become more and more relevant for machine tool applications as the dynamic loads get increased due to an always ever increasing demand for productivity. One of these systematic dynamic deviations is the so-called inertial cross-talk as mentioned in ISO/CD 230-8.23 which consists of displacements perpendicular to the intended direction of motion owing to a lateral offset between the driving force and the centre of mass (CM), which causes a tilting motion during acceleration and deceleration. The tilting causes an orthogonal deviation of the tool center point (TCP) depending on the axial TCP offset from the centre of mass (see Figure 1). Ordinarily in the development of machine tools structures inertial cross talk should be minimized as far as possible [1].

Caused by the application, work-space accessibility and restraints concerning cost, for a large number of cases inertial cross-talk can not be fully eliminated by conceptual means only [2]. For these numerous cases the procedure described in this paper shall be applied.

This procedure consists of measuring the systematic cross-talk values and then using the derived proportional factors for the displacement compensation. Due to the linear nature of the inertial cross-talk phenomena a position and

movement dependent generation of additional superposed axes movements can be applied.

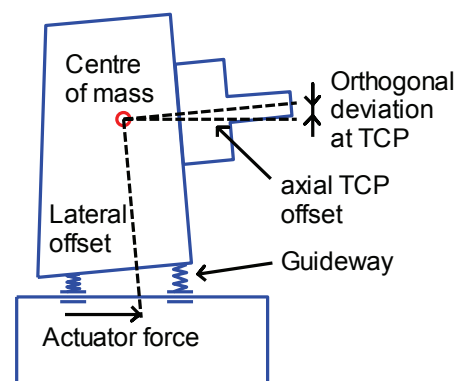


FIGURE 1. The figure shows the principle of cross-talk.

## METHODOLOGY

This chapter explains the single steps required to build a cross-talk model for cross-talk compensation on an industrial numerical control.

### Measurement

Firstly the perpendicular displacements caused by acceleration (or deceleration) have to be measured. An appropriate measurement system is the grid encoder from the Heidenhain Company [3]. Here the axial and the lateral components of motion can be captured simultaneously with moderate practical effort. For a complete compensation of cross-talk on a machine tool every axis has to be accelerated and every orthogonal direction has to be measured individually. In this chapter the movement and measurement process is shown for one specific acceleration direction only. The measurement is done for one specific orthogonal direction only. To be able to find a proportional factor for a specific deviation (example EYX for X-axis acceleration) and machine configuration in the working volume, several different set-point accelerations have to

be defined. Exemplarily the acceleration in Figure 2 is changed to 50, 100 and 200% of the suggested maximum acceleration for displacement over 100mm.

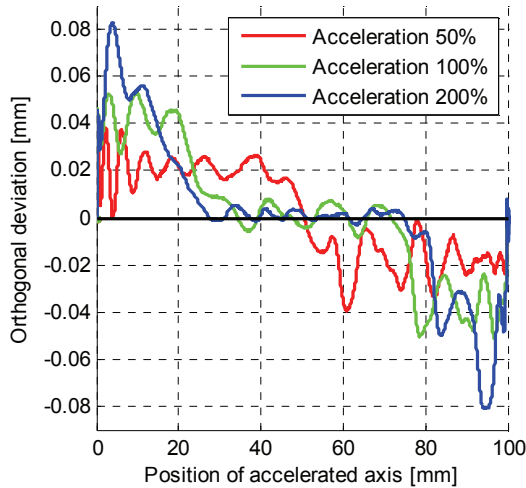


FIGURE 2. Grid encoder measurement with different maximal accelerations defined in the NC. The abscissa shows the positioning movement over 100mm. The ordinate shows the orthogonal deviation mainly caused by cross-talk.

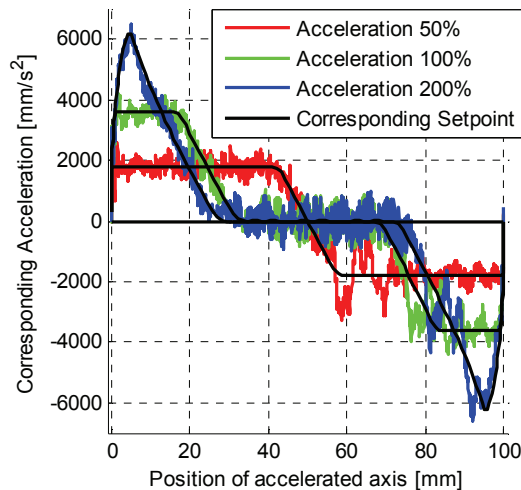


FIGURE 3. Different measured accelerations over the position of the movement. The solid black lines indicate the set-point accelerations.

### Proportional Factors

Figure 3 shows the grid encoder measurements and the corresponding set-point accelerations over the positioning movement. Comparing the acceleration profiles with the orthogonal deviation profile in Figure 2 some correlation becomes obvious [4]. Cross-talk is proportional

to the acceleration as is explained in Figure 1. This proportional factor can be determined through a linear fit (trend) in acceleration to cross-talk plot as shown in Figure 4. By plotting the acceleration versus the orthogonal deviation the linear correlation becomes obvious.

For the linear fit, all the measurements of different accelerations are put together; thereby some measurement filtering is needed. A measured acceleration never goes to zero, thus measurement points with low accelerations do not represent the cross-talk effect and therefore should not affect the linear fitting process. Therefore these points are neglected as described in Figure 4 by defining a lower boundary for acceleration. A lower boundary for the orthogonal deviation is defined to ignore non-cross-talk effects in the fitting process. Additionally all the measurement points from 25 to 75mm are neglected too (Figure 2 and 3). This proportional factor has to be determined for every measured axis configuration of the machine tool.

Figure 4 contains additional information about the possibilities of the cross-talk modeling. The span of the orthogonal deviation on the ordinate-direction describes the amount of orthogonal errors that can't be modeled. Taking a short look at Figure 2 it becomes obvious that excited free oscillations can't be compensated. In contrast to them, the cross-talk which appears to be a forced oscillation (proportional to the acceleration in Figure 3) can be compensated.

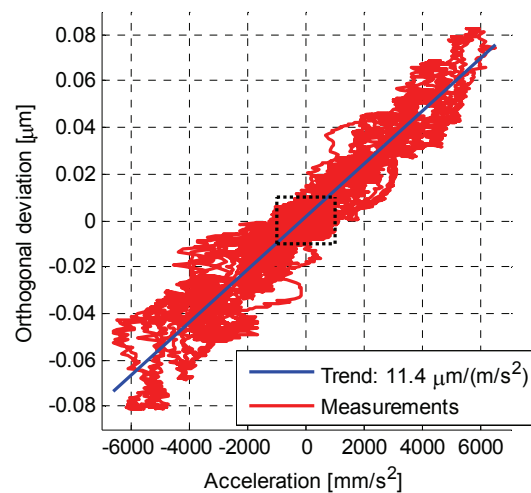


FIGURE 4. 2D representation of measurements; orthogonal deviation versus axial acceleration. The trend-line (blue) shows a linear fit of the data. The dotted area shows points which were neglected for the trend line.

### Model Fit

According to the effects described in [1] an axis-position (machine configuration) dependant model can be created and parameterized by the measurements. The offset of the tool center point from the center of mass (axial TCP offset) as well as the distance of the driving force to the center of mass (lateral CM offset) do influence the cross-talk behavior.

TABLE 1. The proportional factor (PF) determined by a set of measurements and calculated from a machine configuration dependant model are shown. (\* indicates a double weighted machine configuration)

Offset		Cross-talk PF [ $\mu\text{m}$ ] / [ $\text{m/s}^2$ ]		
CM lateral	TCP axial	Measurement	Model	delta
Back	Small	0	-0.3	-0.3
Back	Medium	3.2	3.5*	+0.3
Back	Large	7.6	7.3	-0.3
Front	Small	3.4	3.1	-0.3
Front	Medium	6.5	6.8*	+0.3
Front	Large	10.8	10.5	-0.3

In the current example the measurement was mainly position dependant but not influenced by the moved mass. The observed influence was taken in account using a linear dependence of the orthogonal position.

### Cross-talk Compensation

The compensation of the cross-talk effect is based on feed-forward control. For a given acceleration set-point curve the cross-talk model is applied and the position deviation calculated. These values are then superposed to the original set-points. Using multiple models at a simultaneous axis movement, the compensation values can be accumulated axis-wise. The cross-talk effects inserted onto the system by the set-point compensation is neglected because of the low acceleration that is required. For successful set-point compensation the demanded acceleration and jerk have to correspond to the dynamic capabilities of the compensating axes.

The basic plant model [5] is used to investigate the transfer function behavior from the set-point to the internal measurement system. As shown in Figure 5, the plant model applied on the compensating movement inhibits the compensation due to its limited dynamics. To resolve this loss a scaling factor is applied to the set-point compensation. Applying the plant model, the loss of compensation can be recovered. To determine the scaling factor the

simulation is compared with the compensation of the cross-talk model.

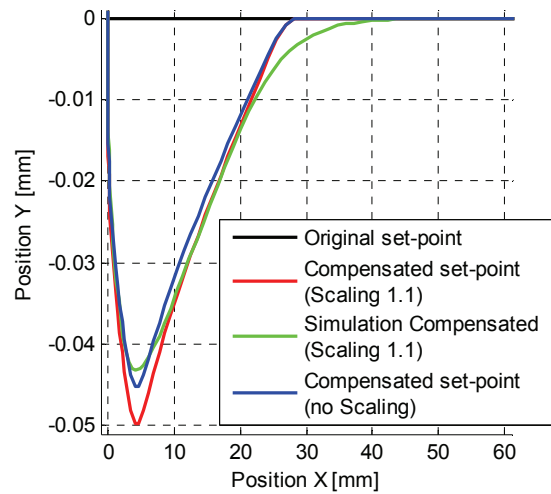


FIGURE 5. Set-point profiles using a cross-talk model for compensation (first part of positioning motion). Calculated compensation in blue, scaled compensation in red.

### RESULTS

The cross-talk compensation described above can be implemented in an actual NC.

### Using Industrial Numerical Control

The simple model described above does allow a machine configuration dependant implementation on an industrial numerical control. For the measurements shown below firstly the original set-point values for the 100mm positioning movement were captured on the Siemens numerical control (Sinumerik 840D). The modified compensated set-point values were then fed back directly as input for the position feed-back controller. The compensation can't be implemented through ISO-NC code due to geometry and feed-rate optimization inside the numerical control.

### Measurement Results

For a corresponding machine configuration, a compensated set-point trajectory was applied on the machine tool. All the settings for the positioning movement, including jerk, acceleration and velocity stayed the same beside the small lateral compensational movements. In Figure 6 the original measurement is compared with the resulting compensated measurement. The results show a reduction of the maximal cross-talk deviation by

about 50% without influencing the dynamics of the machine tool.

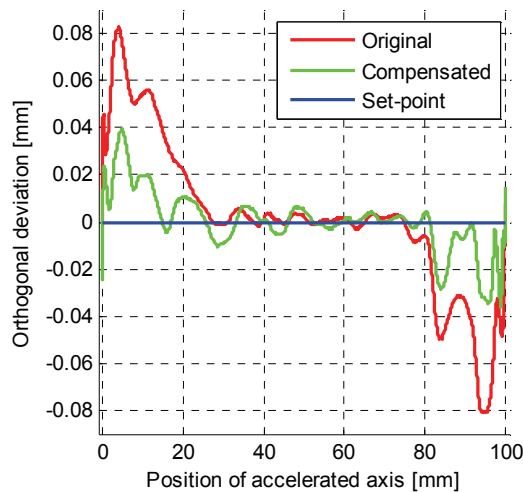


FIGURE 6. Measured cross-talk deviation for the non-compensated system (red), for the compensated system (green). The programmed set-point is indicated blue.

## CONCLUSION AND RECOMMENDATIONS

### Summary

This paper gives a step by step description for a compensation of inertial cross-talk on an industrial machine tool. The first step is a dynamic machine configuration dependent measurement in representative positioning and measurement directions. These measurements are performed with different maximum accelerations. Based on these measurements a proportional factor describing the ratio of the orthogonal deviation depending on the acceleration and the machine configuration can be determined. The given drive dynamic can be taken into account by using a scaling factor. For a given set-point trajectory (including acceleration profile) the compensation can be calculated and feed back in the industrial numerical control.

The step by step procedure is applied in an example for a single positioning direction and an over 50% reduction of the maximal cross-talk effect was achieved.

### Discussion

The result shown in Figure 6 clearly leaves potential for improvement. The compensated trajectory still has cross-talk characteristics, meaning acceleration and deceleration lead to a definable orthogonal derivation direction.

The proportional factor (see Figure 4) is sensitive to the selection of points for the trend calculation. The observed sensitivity in the example is  $0.5 \mu\text{m per m/s}^2$ .

## Recommendations

In the chapter of compensation the additional scaling of the compensation is suggested because some of the compensation is lost due to actuator dynamics and non-linearity. An alternative approach could be the use of an inverted model of the plant.

## ACKNOWLEDGMENT

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