In- and Cross-Talk Evaluation of Different Machine Concepts

S. Thoma[1], T. Haas[2], H. Nguyen[1], S. Weikert[1,2], K. Wegener[1]
[1]*Institute for Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology (ETH) Zurich, Switzerland*
[2]*Inspire, Transfer Institute for Mechatronic Systems and Manufacturing Technology, Zurich, Switzerland*

Abstract

Five axis machine tools are commonly used in manufacturing of sculptured surfaces which leads to increased demands for dynamic accuracy. The R-Test measurement device enables an efficient evaluation of dynamic deviations, i.e. Cross- and In-Talk at the tool centre point (TCP) position. Cross- and In-Talk deviations are strongly dependent of the actual axis configuration and the parameterisation of the numerical control (NC). Depending on the machine tool configuration and the structural stiffness, the readings of the internal measurement system of the machine tool can differ significantly from the TCP movements.

This paper presents a comparison between readings of the internal measurement systems and real TCP displacements concerning Cross- and In-Talk deviations for different machine tool configurations.

1. Introduction

In order to carry out relative motions of the TCP in the work piece coordinate system, forces have to be applied by the drives to overcome the frictional, the inertial and the gravitational forces and the forces applied by the process. Depending on the chosen configuration of the drive forces (F_a), the centres of inertia and the location of the measuring systems, systematic distortions can be stated. The systematic nature of these distortions can be described as inertial Cross-Talk and inertial In-Talk as well as frictional Cross-Talk. The inertial Cross- and In-Talks can be explained as follows: The offset between the centre of gravity and drive force input location (ΔYF_a) causes momentum acting on the machine tool structure also stated in [1], [2] and [3]. Figure 1 schematically shows the drive force Fa introducing the acceleration of the table, inducing a momentum, which leads to tilt motions and causes straightness deviations (EYZ e.g.) linked to inertial Cross-Talk and positioning deviations (EZZ e.g.) linked to In-Talk, depending also on the stiffness of the guide way system (k_{Yi}, k_{Ai}) .The corresponding equations are given by (1) and (2). The variables are shown in Figure 1. Due to the absence of measurement systems located directly at the TCP, these dynamic displacements at the TCP can't be compensated on-line by common closed loop drive control.

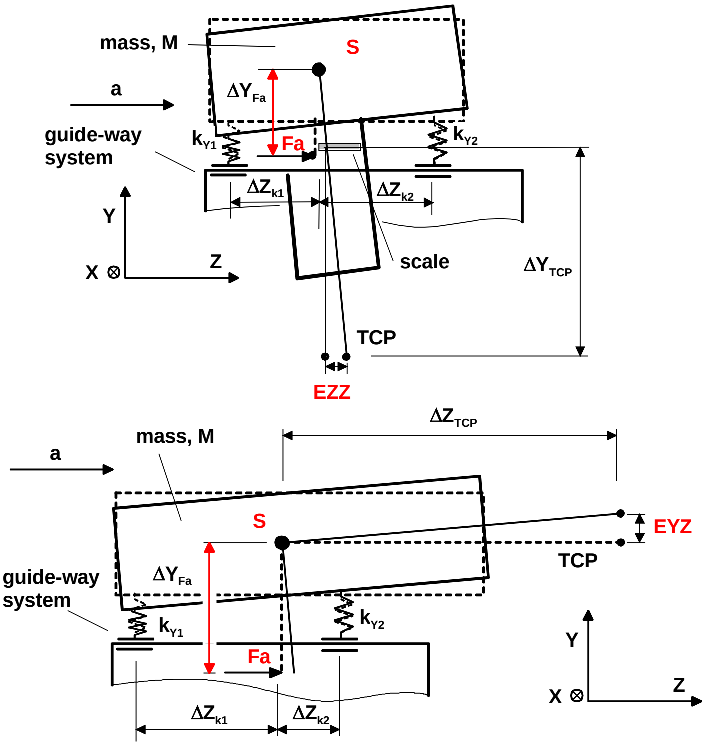

Figure 1: Illustration of effects: inertial in-talk ($EZ\ddot{Z}$, top), inertial cross-talk ($EX\ddot{Z}$, bottom)

$$EZ\ddot{Z} = \frac{F_a \Delta Y_{Fa} \Delta Y_{TCP}}{\sum_i k_{Y,i} \Delta z_{k,i}^2 + \sum_i k_{A,i}} \qquad (1)$$

$$EY\ddot{Z} = \frac{F_a \Delta Y_{Fa} \Delta Z_{TCP}}{\sum_i k_{Y,i} \Delta z_{k,i}^2 + \sum_i k_{A,i}} \qquad (2)$$

Another significant dynamic effect which appears due to frictional effects instead due to inertial effects is illustrated in figure 2: The interaction of drive forces F_f which here are compensating velocity related friction forces at the guide-ways lead, similar to the acceleration forces in case of the inertial Cross-Talk to a momentum, which leads to tilt motions and causes straightness deviations EYZ e.g. [5]. In contrast to their inertial counterparts, these frictional effects are purely velocity dependent. Due to the fact that friction forces may occur in a plurality of dependencies from the velocity such as viscous, coulomb of following Stribeck's law, the direct relationship to the velocity cannot be used for quantification of this effect.

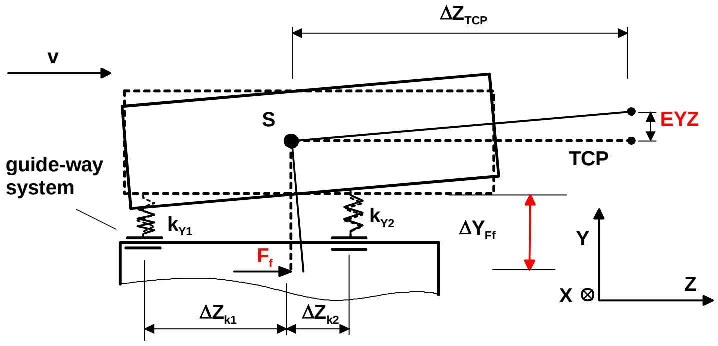

Figure 2: Illustration of frictional cross-talk ($EY\dot{Z}$)

$$EY\dot{Z} = \frac{F_f \, \Delta Y_{Ff} \, \Delta Z_{TCP}}{\sum_i k_{Y,i} \Delta z_{k,i}^2 + \sum_i k_{A,i}} \qquad (3)$$

On a mechanical system, the effects illustrated above appear any time when a motion is carried out. In order to quantify these effects which can be seen as significant property of an axis system, the evaluation of small circular path has been proposed [3]. In this paper, a number of measuring results are shown including interpretation. In addition to [3] frictional effects according to (3) are also discussed.

2. Measurement method

Due to the systematic nature of these effects a method for the efficient derivation had to be stablished. As explained in detail in [3], the R-Test turned out to be a useful tool for this. The measurement system, the motion used for the measurement and the evaluation method applied are briefly outlined next. For a detailed explanation of the evaluation, please refer to [3].

2.1 Measurement system

The R-Test [4] is a measurement setup, where the external measurement at the TCP is carried-out using a precision sphere and by three incremental probes mounted perpendicularly to each other (see figure 3).

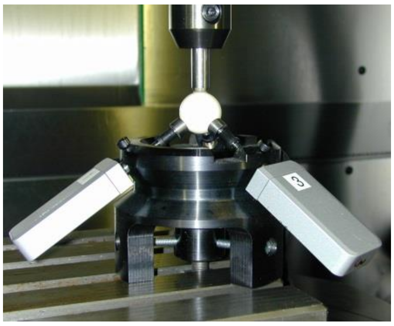

Figure 3: R-Test setup

The spatial measurement range is ±3 mm, the measurement uncertainty of the R-Test measurement setup is U(k = 2) = 2.8 µm. The internal measurement is provided by closed-loop position measurement of the machine tool.

2.2 Measurement motion

For the assessment of the inertial Cross- and In-Talks, a series of circles of 2 mm radius in the three main planes of the machine tool are used. The circular motions were measured in clock-wise and counter-clock-wise sense of motion at different programmed feed-rates. In contrast to single axis pendulum motions as used in [1] circular movements lead to reduced excitation frequencies due to their harmonic nature. Nevertheless the reachable acceleration values are high, while the excitation frequency is far below the values of typical structural natural frequencies of machine tools: A radius of 2 mm and a feed-rate of 6000 mm/min lead to 5 m/s^2 acceleration and an excitation frequency of 8 Hz.

2.3 Evaluation method for inertial effects

As explained in [3] in detail, the orientation of least square planes in the three main coordinate planes lead to the six Cross-Talk parameters $EY\ddot{X}$, $EZ\ddot{X}$, $EX\ddot{Y}$, $EZ\ddot{Y}$, $EX\ddot{Z}$, $EY\ddot{Z}$. A comparison of the main axes of ellipses to the trajectories measured with the R-Test and the internal measurement systems lead to the three In-Talk parameters $EX\ddot{X}$, $EY\ddot{Y}$, $EZ\ddot{Z}$. All these nine parameters have $\frac{\mu m \cdot s^2}{m}$ as unit as they describe displacements proportional to accelerations. It has to be added, that the In-Talk parameters are not influenced by the control of the machine. In contrast to the Cross-Talk parameters the actual internal measurement values are required which may be difficult.

To conclude the spatial effect of the In- and Cross-Talks in 3D, $E3D_{\max}$ is calculated which describes the maximum deviation of these effects in the work-piece. For the square root of sum of squares of the In- and Cross-Talk parameters as absolute values per direction is calculated following (4).

$$E3D_{\max} = \sqrt{(|EX\ddot{X}| + |EX\ddot{Y}| + |EX\ddot{Z}|)^2 + (|EY\ddot{X}| + |EY\ddot{Y}| + |EY\ddot{Z}|)^2 + (|EZ\ddot{X}| + |EZ\ddot{Y}| + |EZ\ddot{Z}|)^2} \quad (4)$$

2.4 Evaluation method for frictional effects

Due to the quite non-linear relationship of the friction forces and the corresponding velocities, the following evaluation procedure is proposed:
The circular clockwise and counter-clockwise movements in each main plane are evaluated individually according to [3]. As resulting inertial Cross-Talk value, the average of the inclinations of the two senses of motion is used.
For the evaluation of the frictional error components, the following aspects have to be regarded: The inertial Cross-Talk values for the different senses of motion in a plane differ solely due to frictional effects. Figure 4 shows schematically the influence of frictional effects in combination with an inertial effect $EZ\ddot{X}$: On the left side of figure 4 viscous frictional Cross-Talk $EZ\dot{Y}$ is superposed, while on the right side coulomb frictional Cross-Talk $EZ\dot{Y}$ is added.

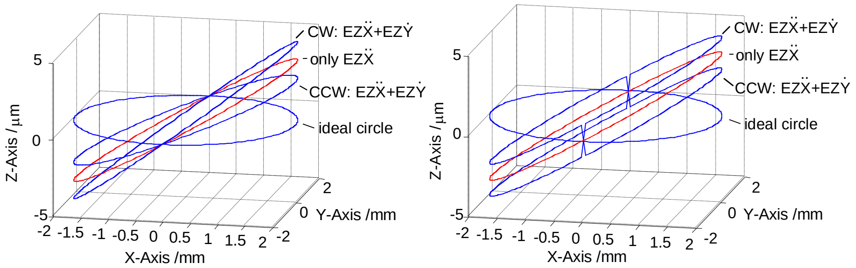

Figure 4: Schematic superposition of inertial and frictional Cross-Talk; left: viscous friction, right: coulomb friction

As can be deduced from figure 4, the use of the least square planes to derive the frictional Cross-Talk parameters is only applicable for the case of viscous friction. In order to cover cases of non-linear friction effects, it is proposed here that the maximal distance of the measurement values contained in the clockwise and counter clockwise measurement points in a main plane are used. To eliminate the systematic influences linked to acceleration, the mean orientation of the least square plane is corrected. Finally, for each main plane a common value for flatness, assumingly not linked to acceleration can be indicated:

$EZ\dot{X}$ and $EZ\dot{Y}$ lead to the flatness of circles in X-Y-plane $\square XY$
$EY\dot{X}$ and $EY\dot{Z}$ lead to the flatness of circles in X-Z-plane $\square XZ$
$EX\dot{Y}$ and $EX\dot{Z}$ lead to the flatness of circles in Y-Z-plane $\square YZ$

3 Measurement results

In this section the results obtained for a number of different machine concepts are shown and discussed. Especially the relation between inertial Cross- and In-Talk and the axis configuration is regarded. In- and Cross-Talk values smaller than 0.2 µm/ms^2 are omitted due to the small effect of these components (smaller than 1 µm at 5 m/s^2) and are labelled as ≈0.

3.1 Universal milling centre

The kinematic chain of the machine tool (Figure 5) can be described in accordance with ISO/DIS 10791-1 [6] as: V [w X’ Y’ b Z (C1) t].

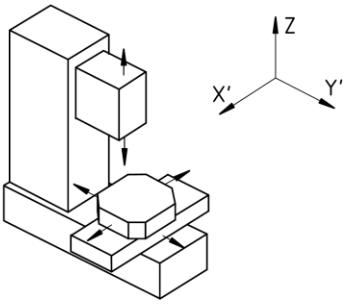

Figure 5: Kinematic (schematic) of the first machine tool under investigation

The evaluation of circular trajectories of 2 mm radius in the three mail planes leads to inertial In- and Cross-Talk values as shown in Table 1.

	$\ddot{X}$	$\ddot{Y}$	$\ddot{Z}$
EX	-1.6	0.84	0.3
EY	≈0	-1.15	0.45
EZ	-0.4	1.8	-9.0
$E3D_{max} = 11.6\ \mu m/ms^2$			

Table 1 In-Talk and Cross-Talk values obtained on first machine concept.

The main component here is $EZ\ddot{Z}$, caused by the large offset of the spindle from the Z guide-way. The values for $EY\ddot{X}$ and $EZ\ddot{X}$ are smaller than $EX\ddot{Y}$ and $EZ\ddot{Y}$ because of the higher length to height ratio of the X-axis.

3.2 Five axis machining Centre 1

The kinematic chain of the second vertical machine tool can be described in accordance with [6] as: V [w C2’ B’ b [Y1 Y2] X [Z1 Z2] (C1) t].

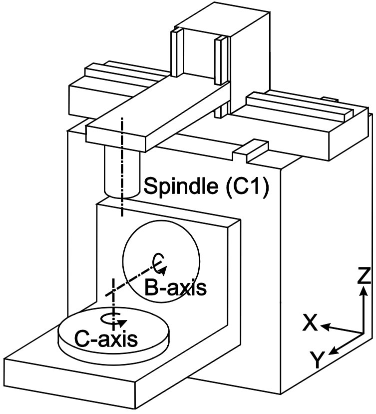

Figure 6: Kinematic (schematic) of the second machine tool under investigation

The evaluation leads to inertial In- and Cross-Talk values as shown in Table 2.

Top of workspace	$\ddot{X}$	$\ddot{Y}$	$\ddot{Z}$
EX	-1.53	0.97	≈0
EY	≈0	-1.60	≈0
EZ	≈0	≈0	-3.20
$E3D\max = 4.4\ \mu m/ms^2$			

Centre of workspace	$\ddot{X}$	$\ddot{Y}$	$\ddot{Z}$
EX	-1.34	1.42	0.22
EY	0.22	-1.70	≈0
EZ	0.43	≈0	-3.94
$E3D\max = 5.6\ \mu m/ms^2$			

Table 2 In-Talk and Cross-Talk values obtained on second machine concept.
top: results obtained on top of the work space
bottom: results obtained in the centre of the work space

For the second machine concept, the Cross-Talk parameters could be minimised using two symmetric drives in Y and Z direction using a so-called Driven in the Centre of gravity DCG concept. In the top position, the Cross-Talk values are below 0.2 $\mu m/m^2$ except for $EX\ddot{Y}$. The increased values in the centre of the work space can be explained by an increased Z-ram overhang.

3.3 Five axis machining Centre 2

The kinematic chain of the third vertical machine tool can be described in accordance with [6] as: V [w C2' A' X b Y Z (C1) t]. The evaluation leads to inertial In- and Cross-Talk values as shown in Table 3.

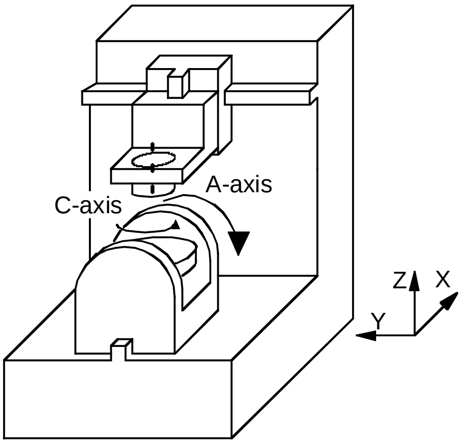

Figure 7: Kinematic (schematic) of the third machine tool under investigation

The evaluation leads to inertial In- and Cross-Talk values as shown in Table 3.

	$\ddot{X}$	$\ddot{Y}$	$\ddot{Z}$
EX	-1.5	-0.2	1.2
EY	≈0	-3.9	≈0
EZ	0.3	≈0	1.4
$E3D\max = 5.1\ \mu m/ms^2$			

Table 3: In-Talk and Cross-Talk values obtained on the third machine concept.

On this machine the In-Talk values are on the same level as for the second machine. Due to a symmetric lay-out, the values for $EY\ddot{Z}$ are small. The significant value for $EX\ddot{Z}$ is caused by the large overhang of the Z-ram, while the small values for $EY\ddot{X}$ and $EZ\ddot{X}$ are caused by the small height to length ratio of the X-table.

3.4 Parallel kinematic Machine

The kinematic chain of the vertical machine tool can be described in accordance with [6] as: V [w b [X1 X2 X3 X4 X5 X6] (C1) t]. The Hexaglide parallel kinematic machine [7], is a concept with linear drives and constant strut lengths.

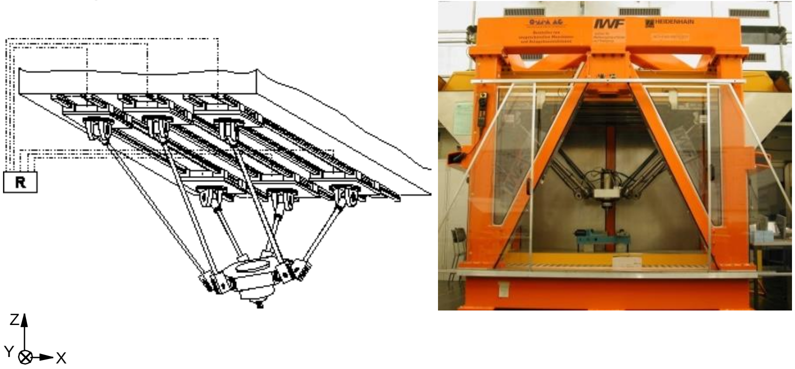

Figure 8: Kinematic (schematic) and image of the fourth machine tool under investigation

The evaluation leads to inertial In- and Cross-Talk values as shown in Table 4. Due to the computed torque control CTC control scheme, the actual internal TCP values required for the In-Talk evaluation have not been available for the measurements.

	$\ddot{X}$	$\ddot{Y}$	$\ddot{Z}$
EX	*	-8	0.3
EY	14	*	3.3
EZ	3	5.5	*
$E3D\max = 21\ \mu m/ms^2$			

Table 4: In- and Cross-Talk values obtained on the fourth machine concept
* No evaluation of In-Talk

The Cross-Talk values are significantly higher than for the other machine concepts which is linked to much larger offsets between drive and inertial forces. Due to symmetry, the $EX\ddot{Z}$ values are significantly lower than the other Cross-Talk values.

4 Conclusions

An evaluation procedure for the assessment of inertial and frictional effects has been proposed.

The procedure for the inertial Cross- and In-Talk evaluation is applied for a number of different machine tool concepts. The dynamic effects could be

traced back to specific design properties of the different concepts such as symmetries, overhangs and height to length proportions e.g. in this paper.
The use of TCP-measurements reveals substantial sources off errors which otherwise remain hidden.

Due to the systematic nature of these effects, their compensation by the numerical control is within reach. Nevertheless the proposed evaluation leads to a objective quantification of the dynamic errors with moderate effort.

The DCG design approach turns out to be an appropriate way to minimise Cross-Talk effects by design.

For the frictional evaluation a procedure is proposed describing the deviations assigned to friction as flatness parameter per main coordinate plane.

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