Dynamic Analysis of a CNC Machine Frame with a Focus on Different Definitions of Ball Linear Guides

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Abstract. This article is written for the purpose of pointing out the problem that is focusing on creation of the FEM analysis by simplification detailed CAD model. Each simplification brings an error into the calculation. If designer do not fully understand to the design and specific simplification method, he can create the error that can lead to serious consequences.

The created computational model shows the simplifications of the CAD model. To analyze response of the frame of the CNC milling machine based on different definition of roller linear guides, through MSC Marc for simulation and analysis, a simplified FEM computational model was created. Four variants of the replacement of the linear guides with the final evaluation of the results of each variant were described.

Introduction

Nowadays, the overall models of machine are made to the smallest details. A virtual prototype can save cost and time during the design phase of today’s machine tools [1]. Unfortunately, this is not always beneficial. Experience suggests that, even when a solid model of the part does exist, it is seldom used directly to create the analysis model but rather the necessary geometry is still reconstructed specifically for the application in hand [2]. Therefore, normally the model is simplified [3,4] and includes only important parts.

Computational Model

Figure 1 shows the CAD model of the standard CNC milling machine. The machine respectively whole CAD model is too complicated, and it is not possible to accurately convert this complex structure into a computational model. Therefore, the irrelevant parts like covers, accessories, etc. were suppressed. The tool carousel and tool changer have been replaced by one solid body representation with the same weight. Ball screw mechanisms have been replaced with rigid rosettes (roller bearings and motion nuts) and linear springs with defined stiffness (screws) see Fig. 2. Replacement of linear guides, which is a point of interest, is described more in the chapter below. The final FE model consists of the seventeen main parts, which are shown including the legend in Fig.3. Mutual connection of all parts was accomplished by aligning appropriately nodes, so the connection is considered to be perfectly stiff.

Geometrically complicated parts have been simplified and meshed with linear tetrahedral elements (tetra4). Symmetrical parts and plates were meshed with linear brick elements (hex8). The main frames, the clamping plate and the rotary table are manufactured from cast-iron. All remaining parts are made of steel shown in Fig. 5. Two computational analysis (static and modal) were used to compare and evaluate the variants. The definition of boundary condition is shown in Figure 6. FIX_XYZ condition is applied in the location, where the CNC center stands on six leveling feet. All elements are defined with gravity acceleration. The representation of this force is suppressed for better clarity of the figure. The cutting forces were calculated for face milling in the X-direction. The definition of boundary conditions is shown in detail on Fig. 7.
Replacement of Linear Guides

Although there are studies focusing on the detailed analysis of contact in linear guides [5] for computational analysis of the machine construction, this method is not suitable. With every detail, the preparation of the model and computation time increases, which is undesirable. The individual subchapters describe four methods of replacement of linear guides.

The First Variant

The first variant of the representation of roller linear guides is executed by means of rigid links see Fig 7. Detail of the replacement for one linear guide is on the Fig. 8. There is always one linear rail and two relevant carriages that are connected. Nodes located at surface, where the rail is fix to the frame, are connected to the one referent node by rigid rosette "RBE2". Also, the same approach was applied at linear carriages. Mutual connection has been realized by total rigid link between referent nodes.
The Second Variant

The second variant of the representation has been realized by simplified FE models of individual parts see Fig 9. Linear rails and carriages are modeled without clearance, rollers, roller redirection unit, front plate, etc. Contact for transmission of forces is ensured by aligning appropriately selected nodes see Fig.10.

The Third Variant

The third variant of the representation is a modification of variant one, see Fig.11 and 12. Replacement of linear rails and carriages is made by rigid rosette "RBE2" connected into one reference node. Difference compared to the first variant is in the area of selected nodes for replacement of linear rails. It is assumed that forces are transmitted on the rail only nearby carriages. Therefore, the representation of the linear rail from the first variant was divided into two "RBE2" rosettes with their own reference node. These individual replacements were interconnected by a spring link with defined stiffness for the perpendicular directions to the linear axis of movement of the linear guide.
The Fourth Variant

The last variant of the representation is based on the variant two see Fig. 13. In this case, FE models are created with minimal clearance, see Fig. 14. At the place of expected contact of the rolling elements with the rail (marked by black ellipses on Fig. 14) individual nodes are interconnected by spring links with a defined stiffness. Stiffness is defined for directions perpendicular to the axis of movement. Emphasis has been placed on the creation of the FE model of the individual parts in order to avoid the connection of the nodal points.

![Figure 13. Replacement of linear guides.](image1)

![Figure 14. Detail of contact definition.](image2)

Results

Deformations of the frame were evaluated on the top of the frame and on the tool (see Figure 3, Node 1 and 2). The displacement of these points is shown in Table 1. Overall displacement is shown on figures 15 to 18 for better imagination. The modal analysis results are presented in Table 2.

Table 1. Displacement of selected nodes.

| Variant | Node 1 | Node 2 |
|---------|--------|--------|
| 1       | x:0,006mm y:0,029mm z:0,019mm | x:0,076mm y:0,031mm z:0,038mm |
| 2       | x:0,003mm y:0,039mm z:0,029mm | x:0,098mm y:0,042mm z:0,049mm |
| 3       | x:0,008mm y:0,051mm z:0,031mm | x:0,124mm y:0,055mm z:0,062mm |
| 4       | x:0,010mm y:0,054mm z:0,036mm | x:0,141mm y:0,060mm z:0,067mm |

![Figure 15. Displacement results of variant one.](image3)

![Figure 16. Displacement results of variant two.](image4)

![Figure 17. Displacement results of variant three.](image5)

![Figure 18. Displacement results of variant four.](image6)
Table 2 Displacement of selected nodes.

| VARIANT 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 208.3      | 304.6 | 436.3 | 527.0 | 652.8 | 680.9 | 79.9 | 88.2 | 98.6 | 102.5 | 119.5 | 123.4 | 173.1 | 192.3 | 243.5 | 264.7 | 279.2 | 299.3 |
| VARIANT 2  | 27.6 | 30.0 | 43.1 | 54.0 | 65.0 | 67.8 | 75.8 | 82.9 | 89.4 | 99.9 | 111.0 | 123.3 | 135.6 | 156.3 | 205.0 | 206.5 | 241.2 | 264.4 | 267.2 | 274.6 | 282.0 | 294.4 | 299.8 |
| VARIANT 3  | 27.4 | 29.7 | 42.4 | 53.6 | 64.0 | 65.8 | 68.1 | 75.6 | 84.1 | 93.9 | 106.6 | 106.8 | 129.5 | 159.4 | 181.2 | 186.4 | 205.7 | 243.1 | 256.4 | 274.5 | 281.2 | 292.4 | 294.4 |
| VARIANT 4  | 27.3 | 29.5 | 42.9 | 50.3 | 59.6 | 65.1 | 67.8 | 75.2 | 83.1 | 89.7 | 99.5 | 102.7 | 127.2 | 141.0 | 144.7 | 174.8 | 181.3 | 205.6 | 243.4 | 246.4 | 274.3 | 276.6 | 282.1 | 292.0 |

The fourth variant is closest to the real solution of linear guides and is commonly used in calculations [6] by other colleagues. Other methods are compared to the results of this method. The disadvantage of this method is its time-consuming preparation.

The first variant was the easiest to prepare and took the least time. Unfortunately, connection of nodes using RBE2 rosettes along the entire length brings into analysis increase of the rigidity. The reason is the property of the RBE2 rigid rosette. This replacement allows movement and rotation of connected nodes only as a perfectly rigid part. And even though the calculation time was a third shorter, it is clear from the results that it cannot be used at all.

Preparing of the second variant is less time consuming than the first option. This method does not add rigidity to the calculation model. This fact is confirmed by the results, which show a decrease in stiffness and approximation with the values of the fourth variant. The "node to node" connection unfortunately neglects the definition of rigidity and damping of the linear guides. Thus, the overall simplification is once again a variant of a rigid links.

The ideal variant appears to be a combination of the first and second variant. Created RBE2 rosettes, which are smaller do not increase rigidity of the machine frame. At the same time, can be created a linear spring with strictly defined rigidity and damping between the reference nodes for individual carriages. The results of this replacement are very close to the results of the fourth variant. Therefore, this variant could be considered for some applications as a possible method for replacement of the linear guides.

Conclusion

On these four variants of replacement, we can clearly see how a relatively simple step can affect the results of static and modal analysis. Therefore, it is important to always check the calculation model by simple calculations and really consider whether the results show the real behavior of the design.

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