The effects of the bending moment upon the mobile element of 
CNC Machine Tools with great distance between slides

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Abstract. CNC Machine Tools with kinematical feed chains with great distance between slides 
(gantry milling machines, cutting machines, carousel lathes etc.) are utilized extensively for 
machining large and heavy parts. In this type of machine, we can observe a specific 
phenomenon where the gravity center of the vertical actuated elements moves in the direction 
of the balancing force for the mobile elements, causing a bending moment to be induced in the 
mobile element (the mechanical coupling between the two kinematical feed chains). This effect 
leads to deformations and in worse case looking of the mobile element during movement, all of 
this has a detrimental effect on machining accuracy and efficiency. In this paper, using finite 
element analysis (FEA) several studies where preformed. A static analysis that calculates the 
stresses, displacements and strains. A modal analysis to determine the first six natural 
frequencies and modal deformed shapes. A harmonic response analysis to determine the 
response of the mobile element structure. This studies will highlight the week points of mobile 
element and will provide the machine tool builder with important information regarding the 
points that need to be address in order to improve the behavior of the mobile element during 
actuation.

1. Introduction
CNC machine tools with kinematic feed chains with a great distance between the slides (gantry 
milling machines, cutting machines, carousel lathes, etc.) are widely used for machining large and 
heavy parts. With this type of machine, we can observe a specific phenomenon in which the center of 
gravity of the vertically actuated elements moves in the direction of the balancing force for the mobile 
elements, causing a bending moment at the moving element (mechanical coupling between the two 
chains kinematic advance). This effect leads to deformations and, worse, to the locking of the moving 
element during movement, all of which have a negative effect on the accuracy and efficiency of the 
machine. A study using finite element analysis (FEA) for this type of deformation is extremely useful. 
This study can be performed by a static analysis that highlights the effects of bending moment on the 
rigidity of the moving element in static loading conditions but the level of accuracy of such an analysis 
is relatively low because this analysis does not take into account the interaction between mechanical 
structure, system control and the dynamics of the machining process [1, 2], so to improve the accuracy 
of the results a dynamic - modal analysis is required to natural frequencies and modal deformed shapes 
of the structure [3]. After the modal analysis, a harmonic analysis can be performed to determine the 
response of the structure to loads that vary harmonically over time. A 3D model for a carousel lathe 
SC14 CNC was created for dynamic behavior analysis of the moving element (cross-rail/ moving 
beam). This model was imported into ANSYS® Workbench for FEA analysis.
2. Initial data and FEA model

2.1. 3D model, material and mesh
Using the drawings and documentation from the machine book of an SC14 CNC carousel lathe, figure 1, a simplified 3D CAD model was created for the FEA calculation. The model respects the overall dimensions and technical parameters of the machine. The elements of the machine are: the frame/bed, the table, the cross-beam/rail, the horizontal slide and the vertical slide, this work will analyze the behavior of the cross-rail/ cross-beam (will call it the mobile element). Due to the fact that the coordinate axes of the machine differ from the coordinate axis system in ANSYS in this paper we will use the coordinate axes in ANSYS, X is the direction of movement of the horizontal slide, Y is the direction of travel of the mobile element and the vertical slide and Z will be used for cutting forces. The material used is: gray cast iron.

Figure 1. SC 14 CNC carousel lathe and Mesh model.  

The mesh is set to default except for the mobile element which uses the “Body Sizing” method for better element quality (element size =60).

2.2. Balancing the mobile element and loading conditions
As can be seen in figure 2, the machine frame is fixed to the ground, the gravitational acceleration it’s on Y axis -9806.6 mm / s², the cutting force of 2000 da N it’s split between a moment of 1200 daN (Y axis) and force on direction –Z of 800 daN for better results.

Because of its own weight, CNC machine tools that actuate the mobile element / cross-rail (with all its attachments) in the vertical plane need to balance the mobile element in order to move it along the vertical kinematic feed chains, this can be achieved by several methods. Here this machine uses a balancing system with two types of hydraulic cylinders. The constant pressure hydraulic cylinders are cross connected to the mobile element by means of cables that are supported by means of hoists. The compensation hydraulic cylinders fixed to the mobile element ends and are cross connected to the constant pressure hydraulic cylinders by cables also supported by hoists, the cables from an X shape with the hoist supported on the fixed cross-rail or the bed [4]. Thus the weight of the cross-rail (2067 kg) + the weight of the horizontal sled (930 kg) + the slide (636 kg) = 3633 kg resulting in a force of 3562 da N that must be balanced. Moving the horizontal slide to the right will increase the pressure in the right compensation hydraulic cylinder fixed the mobile element and this will tension the cables on the right side of the machine and relaxing the cables on the left side, same applies for left movement of the horizontal slide [4].

2.3. Position of the vertical slide support
The maximum horizontal movement of the vertical slide support on the cross-rail/mobile element is 1050 mm, from this 3 cases where selected. Case 1 in with the vertical slide support centered, 525 mm on X axis from limiter. Case 2 the slide it at maximum right, 1050 mm on X axis and Case 3 the slide
it’s at maximum left, 0 mm on X axis, at limiter. For all three cases the cross-rail will be at a maximum high of 800 mm Y axis since it represent the most unfavorable case.

3. FEA analysis

3.1. Static analysis

A static analysis calculates the effects of constant loading conditions on the machine, while ignoring damping effects. The result represent the rigidity of the machine relative the analysis coordinate system.

This paper will study the behavior of the mobile element for the above mentioned cases. For cases 2 and 3 only the total deformation of the mobile element will be shown.

In figure 3 we can see that the maximum deformation occurs at the vertical support slide, this occurs because the vertical slide extends too much out of the support and acts as a cantilever beam (the most unfavorable case). The deformation at the level of the mobile element is relatively small for cases 1 and 2, and large for case 3, which highlights the need to optimize the structures of the vertical slide and vertical slide support.

3.2. Modal analysis

A modal analysis was preformed to determine the first six natural frequencies and modal deformed shapes, it is the most fundamental of all types of dynamic analysis and allows the structures designed to avoid
resonant vibrations or to vibrate at a specified frequency. Highlights how a structure will respond to different types of dynamic loads and is the basis of the following other dynamic studies like harmonic, dynamic transient. The results in figure 4, figure 5 and figure 6 highlight the first 6 fundamental frequencies of the mobile element, so for case 1 as we can see in figure 4, the first fundamental frequency was 65.567 Hz and the maximum deformation of the mobile element occurred at 258.49 Hz figure 6. Figure 7 shows the first 6 fundamental frequencies for cases 2 and 3, as well as the maximum total deformation.
3.3. Harmonic response analysis

After performing the model analysis and identifying the first 6 fundamental frequencies with their corresponding deformation modes, a harmonic analysis was performed using the module from ANSYS Workbench. Harmonic analysis is able to determine whether the structure of the moving element will successfully overcome the resonance and harmful effects of forced vibrations. A frequency range was set between 0 and 500 Hz, based on modal analysis. A constant dampening ratio of 2% was used. In this analysis, the structure of the machine was excited by a series of harmonic forces that occur between the work-piece and the cutting tool.

Figure 7. Highest modal deformation for cases 2 and 3.

Figure 8. Frequency response directional deformation – Case 1.

Figure 9. Frequency response directional deformation – Case 2.
As we can see from figure 8, figure 9 and figure 10 the largest deformations occur at low frequencies 175 Hz ÷ 250 Hz on Y direction for all 3 cases. Deformations in the X and Z directions were not included, as they are much smaller.

4. Conclusions
From the analysis of the result shows above we can draw some conclusions regarding the behavior of the moving element and points that need to be addressed in order to improve the static and dynamic behavior of the moving element during machine operation. Thus, from the static analysis we can see a problem at the level of the vertical slide and vertical support both that deform significantly under their own weight because of the lack of a balancing system (problem more accentuated at the vertical slide). As can be observed from figures 3, 6 and 7 the issues with vertical slide and its support affect the mobile element (cross-rail) creating elastic deformation at the guideways level. Solving this requires the optimization of the mobile elements structure or better adding a force balancing system for the vertical support and redesigning if the vertical slide. Even so the bending moment at the mobile element level that occurs because of the vertical slide supports horizontal movement it’s within the machine tool precision grade.

5. References
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