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Structural Analysis And Design Optimization Of A Machine Tool Structure Under Static Loads Using CAE

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Abstract: In today's turbulent economy and global marketing machine tool manufacturing companies are striving hard to maintain their competitive edge by developing innovative design to cope up with the modern production requirements like high precision, accuracy and reliability. Thus, machine tool structure development plays an important as they have decisive influence on the parameters that define the capability of machine, motion accuracy, the productivity of machine and quality of machining. This can be achieved by designing the structure with optimal static and dynamic stiffness. In present day designing structural components of machine is targeted to optimum the weight of machine structure while static and dynamic mechanical properties are maintained with desired threshold values. One of the methods to carry out this is through Finite Element Analysis. In the present study structural analysis of the Double Column Vertical Machining Centre is carried out using Pro-e works software. The analysis involves static deformations and strain in structure that is bearing the static forces and design solutions are proposed to optimize the machine structure with maximum deformation in order to have optimum static stiffness, so that balance between productivity and accuracy is achieved. Stiffness of the machine structure for static loads is evaluated by modelling the columns, crossbeam, and cross-slide and ram assembly. Percentage contribution of all the structural members towards the overall deflection at the tool tip is determined. Ram is found to be the important member contributing to the overall deflection at tool tip. Hence detailed analysis of the ram carried out. Various design alternatives are studied to optimize the ram with the objective of increasing its stiffness with minimum weight addition or maintaining same weight with respect to existing ram and decreasing the tool point deflection which in turn increases the stiffness of machine.

Index Terms **– Cross-Slide, Cross-beam, Column (LH) and Column (RH), solid works (3D-modelling tool).**

I. INTRODUCTION

Machine tools are machines that give special forms to the materials in desired shapes and tolerances. These can be metal forming, machining, welding, and casting machines or plastic processing machines, non-traditional manufacturing machines. Manufacturing has always been the key to success among nations in the world economy. Manufacturing is the industrial activity that changes the form of raw materials to create products. New technological developments and market demands have major impacts on manufacturing. As a result, several shifts in the focus of manufacturing processes can be observed, which can be conveniently divided into two major epochs: (1) Pre-computed numerical control, (2) Computer numerical control (CNC). The emphasis on cost-effective production was supplemented with a focus on improved product quality in the CNC epoch. CNC Machining Centres provides necessary tools for easier integration/automation which, in turn, contributed to manufacturing of a product family on the same system at a faster rate reducing production time. Machining centres are the computer numerically controlled machines, which consists of a single or two machine tools with specific features of an automatic tool changer (ATC) and capable of performing number of operations such as drilling, tapping, boring, turning and milling etc., on the work-piece. In these machines jobs need to be clamped on the table only once or twice depending on the complexity of job, the machine then perform a variety of operations on all jobs.Machine tools have been greatly improved during the last decades and are still challenging some new developments such as higher machining speed, precision, and productivity, especially in reducing time-to-market. In order to meet the goal, many researchers have been done on structure and control of machine tools. The main functions of the machine tool structure include, the Ability of the structure or the bed to resist distortion caused by static and dynamic loads, Stability and accuracy of the moving parts, Wear resistance of the guide way, Freedom from residual stresses, Damping of vibration etc. Regarding machine tools, the structure is one of the critical factors to hold the machining speed, precision, and productivity. Moreover, it is critical that the suitable concept of the structure is chosen in the conceptual and fundamental design stage process because 80% of the final cost and quality of a product are designed in this phase. Therefore, to design a suitable machine tool structure with high static and dynamic features is very essential.

II LITERATURE REVIE

The various works are carried out in static analysis, Modal analysis of Structural machine. Among which few are categorized and discussed below.

Y. Atlantis, C.Brecher, M.Weck, It covers various aspects such as analyzing the structure of machine tools, conducting experiments to calibrate them, studying their movement patterns (kinematics), and optimizing the different components of these tools. The paper also discusses the use of advanced computer models to simulate the kinematics, dynamics, and control techniques of machine tools, taking into account the interaction between the machine, its controller, and the disturbances caused by the cutting process. **[1]**

D.Spath, W.Neithardt ,C.Bangert The study primarily aimed to enhance the structural design of a 3-axis micro milling machine by introducing two robust outer ribs that converge towards the top and thicken at the edges. This design modification effectively increased the stiffness of the machine's column, leading to notable improvements in its dynamic performance and natural frequencies. The resulting enhancements positively impacted the machine's ability to perform intricate milling tasks with higher precision.. **[2]**

A. Cowley and S. The evaluation of the program's accuracy involved applying it to simple plate and box structures under various loading conditions and comparing the results with experimental measurements for a knee-type milling machine. The comparison demonstrated good agreement between the finite element-based beam model and the experimental values, indicating its reliability **[3]**

A.C.Stepehen and S.Taylor The paper emphasizes the advantages of analytical techniques, specifically the flexibility method and stiffness method, over the finite element method in structural analysis of machine tools. It highlights that the finite element method, which employs displacement method, is prone to high redundancy when representing structures as assemblies of plate and beam elements. **[4]**

Masamitsu Nakminami, The paper focuses on the design methodology for compound multi-axis machine tools, aiming to create an optimal basic structure prioritizing high accuracy and productivity. The proposed design features a box-in-box structure, a moving column along the Y-axis, and a boring machine structure. These structures are evaluated using the Finite Element Method (FEM) to analyze factors like static rigidity, dynamic characteristics, and movement accuracy. **[5]**

II. METHODOLOGY

Detailed modelling of the structural assembly comprising of Ram, Cross-Slide, Crossbeam, Column (LH) and Column (RH) is modelled in solid works (3D-modelling tool). The modelled assembly is imported to FEA workbench. The materials for respective module are assigned the constraints are added to simulate the real static condition of machine structure.

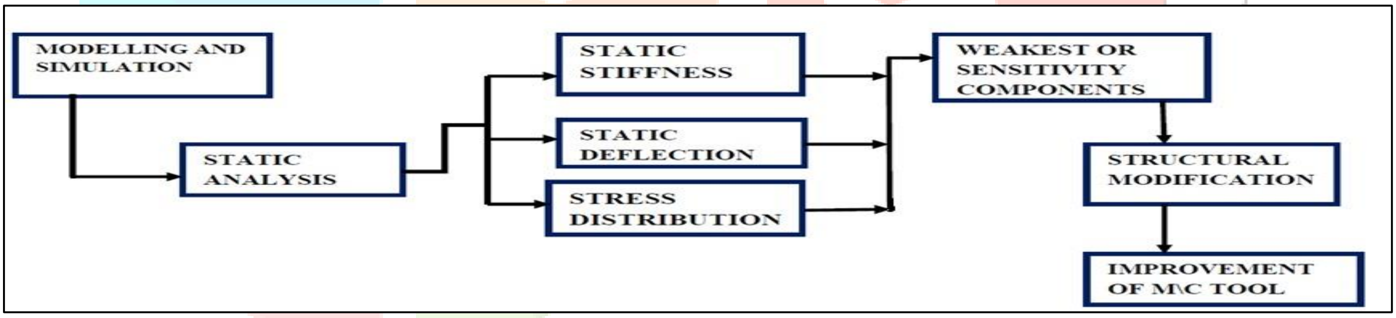


Fig.1 Methodology of Analysis of Machine Tool Structure.

The load is applied at the tool tip only in this method. The deflection measured at the tool point reflects the stiffness of the detailed module which is an elastic body. Since each model is constrained at same locations the deformation of modules is comparable. The weaker and stronger modules are identified. The weakest part is modified for best possible alternative is suggested. The fig shows the flow Chart of methodology used in study.

III. PROBLEM IDENTIFICATION AND LIMITATIONS

Points regarding the design considerations for the machine tool structure, specifically focusing on a double column vertical machining center with X/Y/Z strokes of 3000/200/950mm:

- System Rigidity: The primary consideration is to ensure high rigidity of the machine tool structure to resist deflections caused by cutting loads. This is crucial for maintaining accuracy during machining operations.
- Lightweight Structure: The structural components should be designed to be as light as possible without compromising rigidity. This helps minimize the force required for acceleration and deceleration, reduces jerk in machine motions, and improves stopping distances and overall machine accuracy.
- Analysis of Static and Cutting Loads: The design process should involve analyzing both static loads (such as self-weight of components) and cutting loads. This analysis helps determine the magnitude and distribution of forces acting on the structure, enabling the design to withstand these loads effectively.
- Balancing Material Hardness and Elasticity: The selection of materials should strike a balance between hardness and elasticity. The material should be able to withstand impact forces while allowing for elastic deformations, thus preventing permanent deformation and ensuring the structural integrity of the machine tool.
- Finite Element Analysis (FEA): A common design approach is to start with an initial design based on experience and then refine it through FEA. Finite element analysis helps simulate and evaluate the structural performance, identifying potential weak points and areas for improvement before the actual construction of the machine.

IV. FINITE ELEMENT ANALYSIS OF MACHINE TOOLS

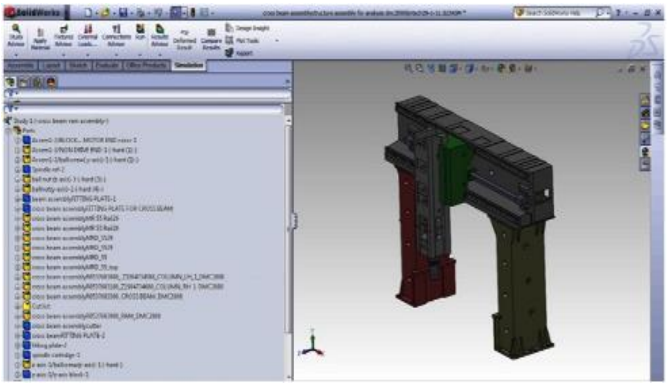


Fig 2. Shows the Material Assigned to Components Fig

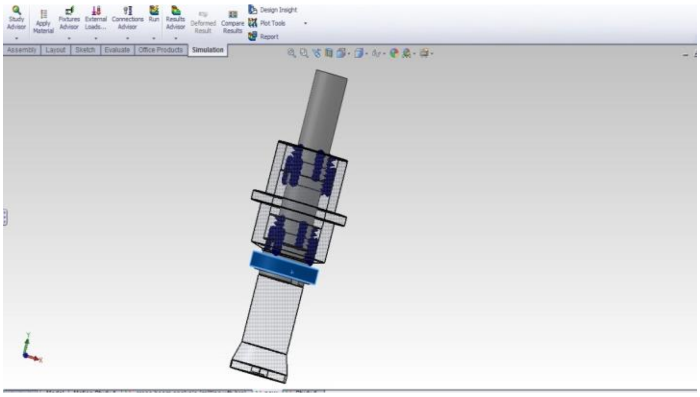


Fig 3. Spindle Assembly view showing Bearing Connector

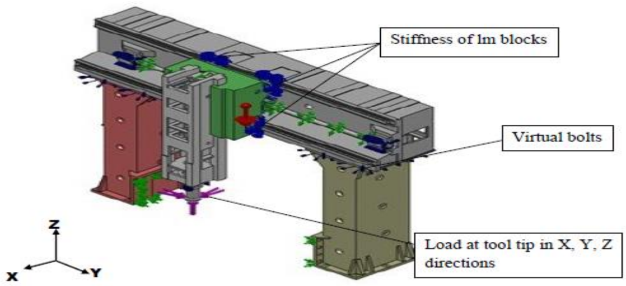


Fig 4. FEA constraints applied to Structural Assembly.

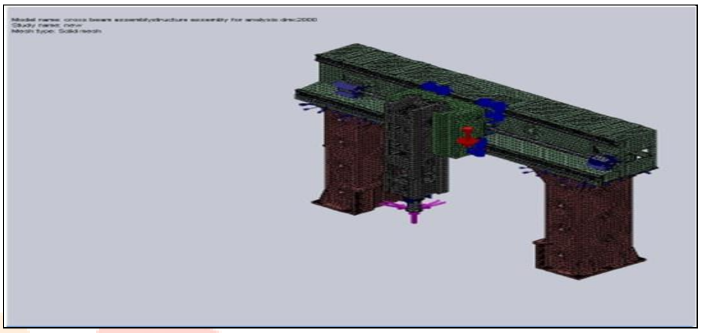


Fig 5. Detailed Meshed Model

The CAD model Ram, Cross-Slide, Cross-Beam, Column-left and Column-right with ball screws and LM-guide ways are modelled and each part is mated to form the assembly of the machine structure in the solid works. The mated assembly is imported to simulation work bench called Cosmos works. Cosmos works is a design analysis system fully integrated with Solid Works. Cosmos works supports IGES and all formats of solid- works. The software provides easy transfer of model to FEA workbench avoiding all tedious, time-wasting tasks associated with creating and analyzing the virtual prototype by CAE engineers, these include CAD geometry translation, geometry clean-up, manual meshing processes, assembly connection definition, and editing of input decks.
The interfaces between cross-slide and cross-beam are linear guides. The model of the 4 lm blocks are established and mounted behind the cross-slide at the location and the corresponding rails (top and bottom) on to cross-beam. The lateral and radial direction stiffness are the given by using springs by LM-blocks and Rails .the spring are given the stiffness are defined from the product catalogue. Stiffness calculation is discussed appendix B.the fig represents method of stiffness assignment for LM-guide way system. The stiffness values of the linear motion system with respect DMC coordinate system is given by the table.

Table 1 Properties of the materials used for machine components

Properties	G4 (Grey Cast Iron)	SG1 (Ductile Cast Iron)	Hard Steel (Is-5120)
Young's modulus Mpa	1.35×10^5	1.74×10^5	2.9×10^5
Density Kg/mm^3	7500×10^{-9}	7350×10^{-9}	5200×10^{-9}
Poisson ratio	0.26	0.29	0.3
Shear modulus Mpa	5.6×10^4	8.3×10^4	8.5×10^4
Tensile strength Mpa	3×10^2	5.86×10^2	7.38×10^2
Compressive strength Mpa	9.6×10^2	8.79×10^2	9.38×10^2
Modules	Column (LH&RH),Cross slide, Cross beam	Ram	Ball screw, LM guide ways

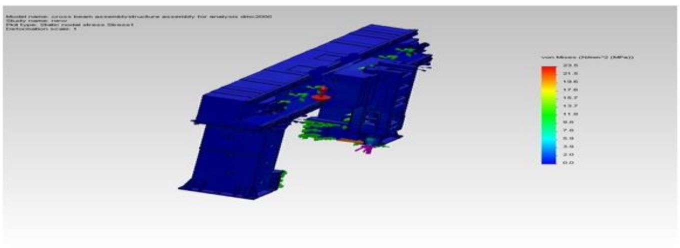


Fig6. Shows the stress plot for the applied load

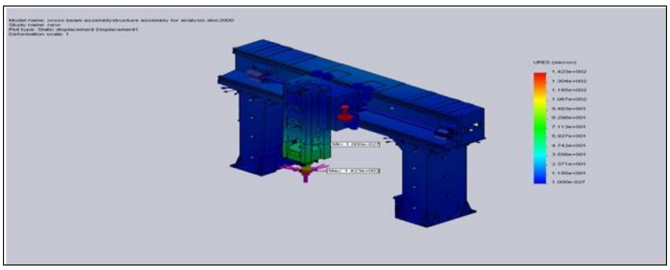


Fig 7.Shows the Resultant Displacement Plot

After applying the boundary condition, the solution of the model under study is carried out in Cosmo works. The displacement along X, Y, Z-direction and resultant, stress are studied:

- Displacement - resultant.
- Displacement along X-direction.
- Displacement along Y-direction.
- Displacement along Z-direction.
- Stress plot

The results of the stress plots and deflection plots are shown in fig

It is evident from the fig 6.9 that the max stress acting on the machine structure assembly is 23Mpa for applied load 736.3Kgf in each direction. The allowable stress is 64Mpa for G4 whereas for SG iron it is 98Mpa [cmti]. Thus the stress in assembly well below the allowable stress and design is safe from strength consideration.

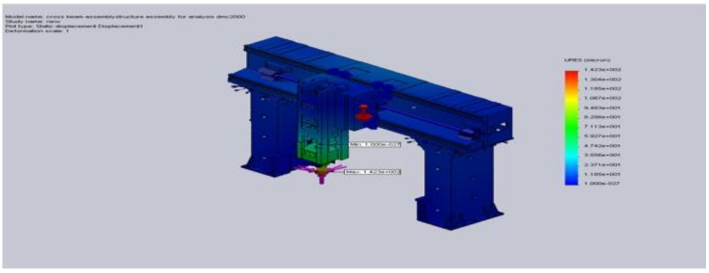


Fig 8. Shows the Deflection in X-direction.

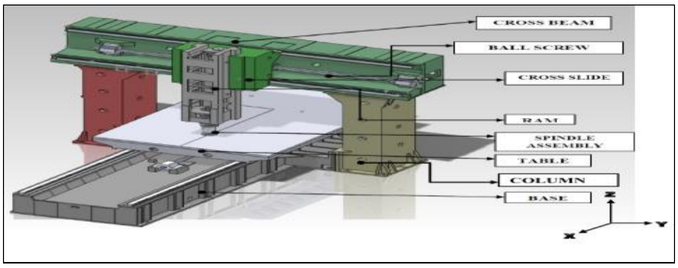


Fig 9: Representative model of structures of DMC 2000N

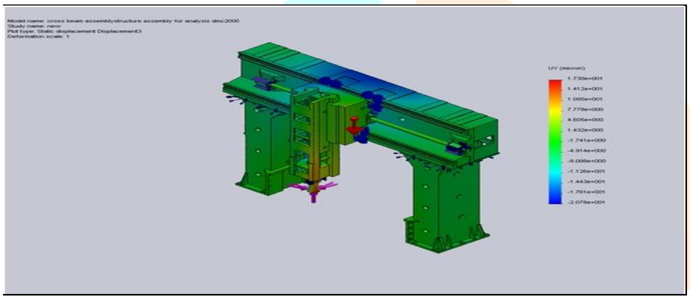


Fig 10 .Shows the Deflection in Y-direction.

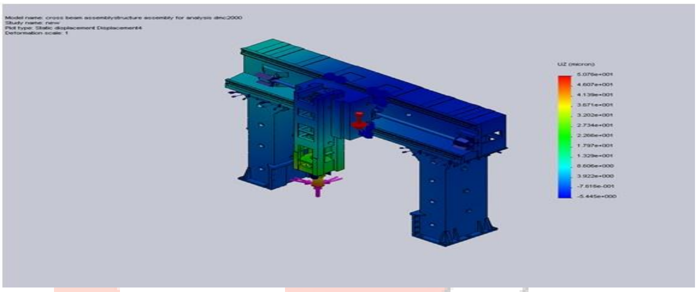
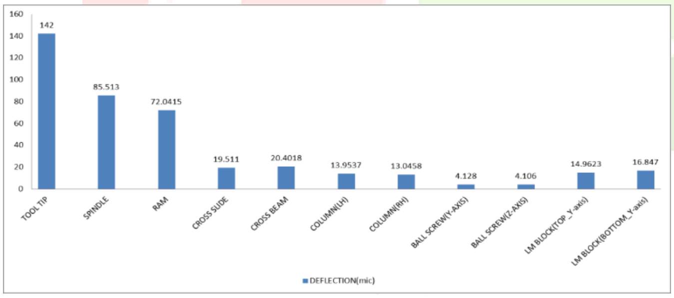
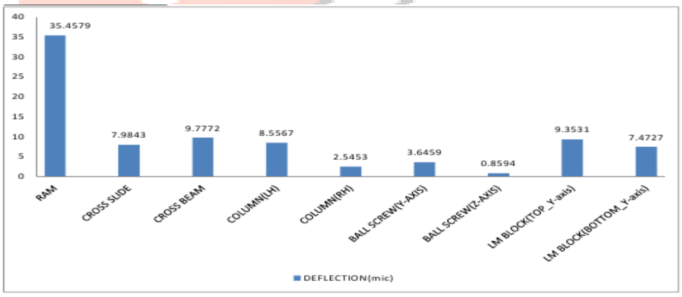


Fig 11. Shows the Deflection in z-directio



Graph 1 shows resultant deflection of each component



Graph 2 Deflection of each component in X-direction

From analysis above further the deflection of each component for resultant and along each directions i.e. X, Y and Z directions are summarized in graphs It is evident from the graphs shown above that the ram is deflected maximum among all the other components thus it is concluded that Ram is the important and weaker part and is taken up for further analysis. Once the exact deflection at the tool point is due to ram is known, the alternative are analysed for achieving optimum reduction in deflection of the ram which in turn decreases the deflection at tool tip. The goal is to obtain high stiffness. The following are design alternatives studied in this regard.

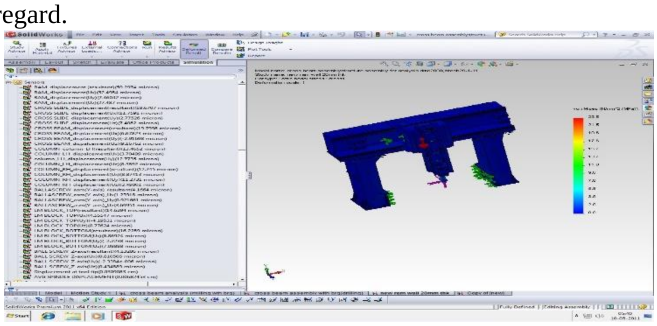


Fig12. shows sensor results for 40mm increase in wall thickness.

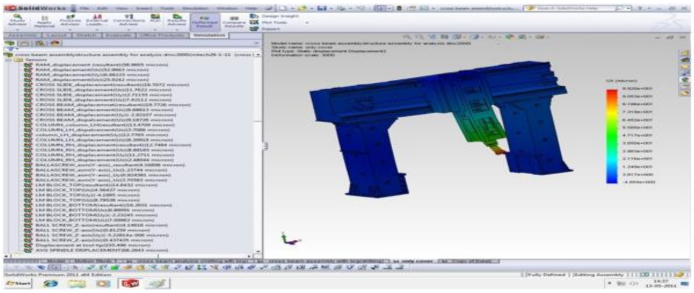


Fig 13. Showing the Existing Ram and Ram

Ram is analysed for the increase of wall thickness of the ram for a length of 675mm from the bottom in the increments of 10mm the fig 6.12 shows the c/s view of the ram showing the walls whose thickness is modified. The graph shows the decrease in deflection with increase of thickness. in this iteration it is observed that with increase in thickness for every 10mm the weight increased by 30kg and deflection reduced by 10µ finally for 40mm (max thickness that can be increased) the deflection decreased to 110µ.. The weight increased is more compared to deflection thus cannot considered. The fig6.13 shows the sensor results of ram for the change of 40mm wall thickness increase. **:** In this case the ram side walls are closed which are used for service using cover plate (well fit plate).the plate is fitted to ram using bolts. The resultant deflection is decreased by 14 microns (72µ to 58µ) and weight increased by only 3%(997.67kg to 1028kg).the tool point deflection reduced from 142µ to 105 µ.The fig 6.14 shows the sensor reports of the ram and tool point deflection.

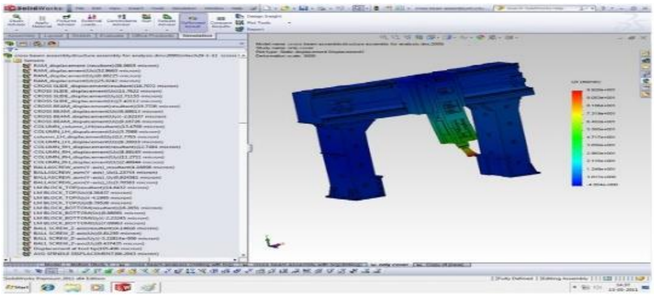


Fig14. Showing the Existing Ram and Ram

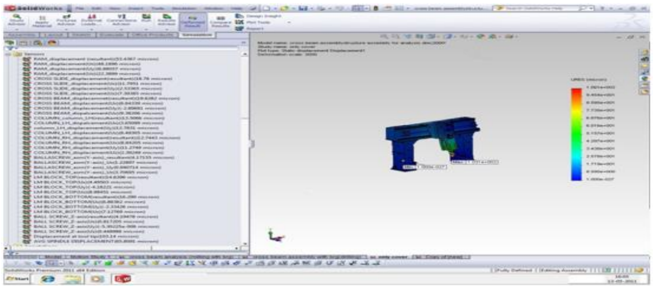


Fig 15. Shows the sensor results of

In this case the ram side opening and front opening both are closed which are used for service using cover plate (well fit plate).The plate is fitted to ram using bolts. The resultant deflection of the Ram is decreased by 20 microns (72µ to 52µ) and weight increased by only 3.25 %(997.67kg to 1050kg).The tool point deflection reduced from 142µ to 100 µ which is the required deflection tolerance as per the user defined data. The fig 6.15shows the sensor reports of the ram and tool point deflection. The torque of the bolts to be 440N-m calculated using formula.In this case the ram material has been changed from SG1 to S1(Cast carbon steel). The selection of material is based on the young's modulus since the deflection is inversely proportional to young's modules refer eqn6. the properties of material is tabulated in table 6.10. The resultant deflection of the Ram is decreased by 14 microns (72µ to 57µ) and weight increased by only 11% (997.67kg to 1124kg). The tool point deflection reduced from 142µ to 102 µ which is the required deflection tolerance as per the user defined data. But the mass of the component is more compared case 3 and deflections are less in case3. At the same time cost of steel is more than SG1 so this case is eliminated. Fig6.16 shows the sensor results of ram and tool tip deflection.The Stiffness of the double column vertical machining centre, the deflection contribution of its structure to the total deflection in the tool tip and redesign of the Ram have higher stiffness and tool point deflection to be within the user's requirement with minimal increase of weight under the static condition.CAE technique (FEA) is used for the purpose. The deformation under external loads of the machining centre assembly like ram, cross-slide, cross-beam, column-LH, column-RH to the total deflection at tool point is found from the static analysis of the assembly structure. Stiffness evaluation indicated that ram is the weaker member. Subsequently, detailed analysis of Ram is carried out and various design alternatives are suggested as discussed in chapter7. The change in deflection and weight during the different iterations are given in the Table.

Table 2 Changes in deflection and weight for different iteration.

Iterations	**Change in deflection in Ram**	**Change in deflection at tool point**	**Change in Weight**
Case1	13µ decrease	20µ decrease	9%increase
Case2	14µ decrease	35µ decrease	3% increase
Case 3	20µ decrease	Decreased by 42µ(142 to 100)	5% increase
Case4	14µdecrease	Decreased by 40µ(142 to 102)	11%increase

V. CONCLUSION

The structural analysis of the DMC2000N is carried out using Pro-eworks2011.Five modules viz., Ram, Cross-slide, Cross-beam, Column-LH, Column-RH are considered for analysing the stiffness by applying FEA.

- The load is applied at the tool tip and the work-piece is transmitted as internal forces through the structure onto the nodes within the interfacial areas, which are between two connecting modules. There is no need to transform the external loading into equivalent forces to be applied at the interfacial areas on the single module. Possible human errors occurring during transformation of loading is reduced to a greater extent.
- Stiffness of the machine centre and contribution of its members to total deflection is evaluated from the results of the analyses, which showed that the Ram is the weakest part among the modules. Subsequently Ram is taken up for optimization with respect to increase in rigidity.
- The ram is redesigned by changing the wall thickness, cover plate design for the opening on the walls of Ram and change of material. Finally, the cover plate design alternative is chosen as best alternative.
- The Ram stiffness is optimized with optimal addition of material compared to existing one by adapting the method of using cover plates (well-fit plates). The Ram deflection is reduced by 20microns with the reduction of deflection at tool point from 142microns to 100microns.now the Ram stiffness have been increased by 20N/µm.

- The primary contribution of the project is to introduce an alternative method for obtaining stiffness of machine tool. The method is highly advantageous in obtaining stiffness of complex machines and assemblies easily and efficiently with higher accuracy than traditional method. The ram is found to be weakest of all modules in X and Z directions. The ram optimization is made possible with optimal utilization of material and also the stiffness of tool is increased which increase the accuracy, productivity of machine.

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