Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2, Issue 5, May -2015

MODELING, ANALYSIS AND OPTIMIZATION OF A MACHINE TOOL STRUCTURES

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Abstract — *This paper works on some of current development of design, analysis and optimization of machine tool column structures. Column, bad, box type housings, table, x-slide, y-slide, z-slides are known as structures of machine tool. In the new economic year and globalization phase, industries are required to manufacture good quality machine tools with optimized performance at the moderate cost. Machine tool structures are the key for quality and high productivity. Moreover, the industries are facing competition internationally due to worldwide globalization of business. One of the primary reasons for low productivity is large mass of the moving parts of machine tools which cannot afford high acceleration and deceleration encounter during operation. In this work is made to solve the problem regards machine tool structures or machine tool industries.*

Keywords – *Structure Material, Structural Bionic Design, Column Stiffeners Arrangement, Parametric Optimization*.

I INTRODUCTION

India is a fast growing country and due to worldwide globalization of business many multinational companies are investing millions of rupees in India. With that it also demands to produce quality product and supplied at the right time. Moreover the quality of the job produced on these machine tools depends directly on the quality and performance of the machine tools produced and some other conditions. To develop good products, design engineers need to study how their design will behave in real-world conditions. To take care of this condition, often analysis and optimization of the proposed design becomes very useful and reliable tool for the design engineer. Due to the large investment in power sector, automobile sector and much more. The demands of very large and heavy components, (pressure vessels, heat exchangers turbine bodies, reactors, large bearing rings, large pipes, electric motor body etc.) and very precise component (linear, piston, pulley etc.) are on peak. To produce these components, demands of metal cutting machine tools are also on peak. Figure 1 shows the import data of metal cutting machine tools in India in last two years [7]. If we can fulfill the demand of today's industry, we can save a lot of valuable money to go out from India.

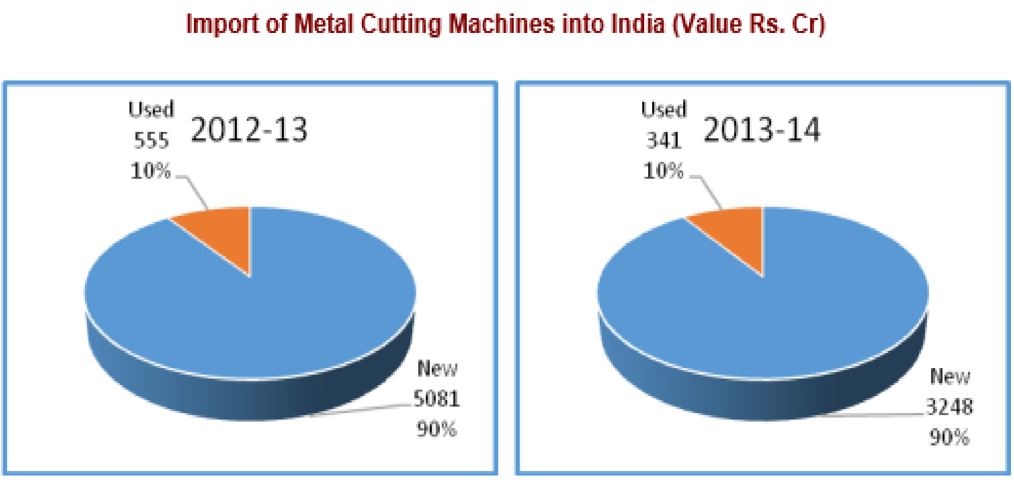

Figure-1. Import data of metal cutting machine tool in India [7]

The term "vertical turret lathe" is applied to machines wherein the same essential design of the horizontal version is upended, which allows the headstock to sit on the floor and the faceplate to become a horizontal rotating table.

II LITERATURE REVIEW

[1] Dail Gil Lee et all : One of the primary reasons for low productivity is large mass of the moving parts of machine tools, which cannot afford high acceleration and deceleration encountered during operation. Moreover, the vibrations of the machine tool structure are among the other causes that restrict high speed operations.
Authors were designed, the slides of high speed CNC milling machines with fiber reinforced composite materials to overcome this limitation. The vertical and horizontal slides of a large CNC machine were manufactured by joining high-modulus carbon-fiber epoxy composite sandwiches to welded steel structures using adhesives and bolts. These composite structures reduced the weight of the vertical and horizontal slides by 34% and 26%, respectively, and increased damping by 1.5–5.7 times without sacrificing the stiffness. Without much tuning, this machine had a positional accuracy of _5 lm per 300 mm of the slide displacement.

[2] Sung-Kyum Cho : Small machine tools have the inevitable drawback of low structural stiffness caused by a low load-carrying capacity of bearing components. Therefore, mass reduction of the components is advantageous to ensure high performance of the machine tools.
A small table-top machine tool structure was designed and fabricated by using carbon/epoxy composites and resin concrete to reduce the weight of the structure, and enhance the structural stiffness and damping capacity. To determine the specifications of the composite materials finite element analyses and vibration tests were carried out. Several machine tool components were fabricated and assembled using mechanical joining and adhesive bonding. Our results showed that the re-designed structure was 36.8% lighter, and the structural stiffness was increased by 16% with higher loss factors (2.82–3.64%).

[3] Ling Zhao : Based on the configuration principles of biological skeletons and sandwich stems, a machine tool column with stiffening ribs inside was designed using structural bionic method.
After the lightening effect was verified by finite element simulation, scale-down models of a conventional column and a bionic column were fabricated and tested. Results indicate that the bionic
column can reduce the maximum static displacement by 45.9% with 6.13% mass reduction and its dynamic performances is also better with increases in the first two natural frequencies. The structural bionic design is effective in improving the static and dynamic structural performances of high speed machine tools.

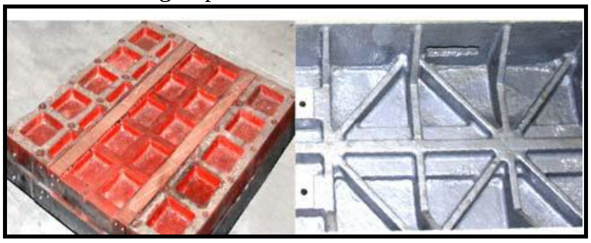

Figure-2. Conventional ribs distribution

[4] Wedad I. Alazzawy : Author studied the static behavior (under torsion and bending loading) of machine tool column. The effects of changing the cross sectional area of the column itself on the deformations (design parameters) was investigated. The adding of stiffeners and changing the stiffeners cross sectional area are also verified. The results show that using of stiffeners can produce a great reduction in deformation of the column structure under the static loading mentioned above. Also using stiffeners with different cross-sectional areas suggest the best stiffener cross-sectional shape can be used to give the minimum deformations of column structure. Dynamic analysis of column involves calculating natural frequencies and mode of different column structure mentioned above, these frequencies are fairly insensitive of adding stiffeners to column structures.

[5] Migbar Assefa: The performance of a machine tool is eventually assessed by its ability to produce a component of the required geometry in minimum time and at small operating cost. It is customary to base the structural design of any machine tool primarily upon the requirements of static rigidity and minimum natural frequency of vibration. The operating properties of machines like cutting speed, feed and depth of cut as well as the size of the work piece also have to be kept in mind by a machine tool structural designer. Author presents a novel approach to the design of machine tool column for static and dynamic rigidity requirement. Model evaluation is done effectively through use of General Finite Element Analysis software ANSYS. Studies on machine tool column are used to illustrate finite element based concept evaluation technique. This paper also presents results obtained from the computations of thin walled box type columns that are subjected to torsional and bending loads in case of static analysis and also results from modal analysis. The columns analyzed are square and rectangle based tapered open column, column with cover plate, horizontal partitions and with apertures. For the analysis purpose a total of 70 columns were analyzed for bending, torsional and modal analysis. In this study it is observed that the orientation and aspect ratio of apertures have no significant effect on the static and dynamic rigidity of the machine tool structure.

III STRUCTURE MODELING OF COLUMN

FUNCTIONS OF MACHINE TOOL STRUCTURE AND THEIR REQUIREMENTS

Machine tool parts, such as beds, bases, columns, box-type housings, over arms, carriages, tables, etc. are known as structures. Basic functions of machine tool structure are as follows:

a) To provide rigid support on which various subassemblies can be mounted i.e. beds, bases.

b) To provide housings for individual units or their assemblies like speed gear box, spindle head.

c) To support and move the work piece and tool relatively, i.e. table, carriage, tail stock etc.

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A. Material for machine tool structure:

Values of some properties of above discussed material are listed in table, below:

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Table .1 Some properties of some structural material – app. Average value [6]

Material	Modulus of Elasticity N/mm^2	Specific Gravity	Specific Stiffness N/mm^2	Coefficient Of thermal Expansion $^0C^{-1}$	Thermal conductivity $Wm^{-1}k^{-1}$	Tensile strength N/mm^2
Cast Iron	117000	7.21	16000	12×10^{-6}	75	230
Mild steel	207000	7.93	26000	12×10^{-6}	80	460
Granite	39000	2.66	15000	8×10^{-6}	0.8	14.7
Epoxy Concrete	33000	2.5	14000	12×10^{-6}	0.5	25

Table .2 Comparison of structure materials [6]

Material	Merits	Demerits
Cast iron	-Possible to cast it in complex and intricate shapes. -Easily machined, hand-scraped and lapped to high degree of accuracy. -Fairly good damping properties -Good anti-friction properties	-Comparatively lower strength -Time and cost taken to produce a finished casting -Technological constraints to produce cast structures i.e. minimum wall thickness -High shrinkage rates during curing -Need anti-corrosion treatment
Epoxy Concrete	-Used for precision machine tool structures -It offers great design freedom same as cast iron -Outstanding damping properties, long term stability	

B. Grey Factor Affecting Strength and Stiffness of Machine Tool Structure:

Machine tool structure is design for higher strength and stiffness, various parameter of machine tool structure profile affect on strength and stiffness are:

- Shape of cross-section.
- Effect of aperture.
- Stiffeners arrangement in structure.
- Effect of bolt arrangement and external vertical stiffeners on column.

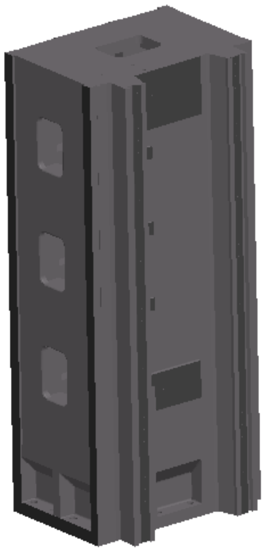

Figure-3. Structure Modeling Of VTL Column

IV FEA ANALYSIS OF COLUMN STRUCTURE

A. Cutting Force Calculations: Drilling [6]

In case of drilling predominant effect is of thrust generated during operation [12].

- In case of drilling, predominant effect is of thrust generated during operation. The thrust force is proportional to the diameter of drill, material to be cut and feed per revolution.
- By taking 100% efficiency of transmission of power from motor to spindle, for maximum cutting force, power at spindle should be equal to power of motor. But for drilling this condition is having another constraint.
- Thrust force, during drilling, is directly proportional to diameter of drill and feed per revolution. So before reaching at the condition of maximum power at spindle, for maximum thrust, constraints are imposed in terms of maximum size of drill and feed per revolution. Thus restricting us in taking size of drill and feed per revolution, thrust force is calculated here. Considering same condition cutting force is calculated below:

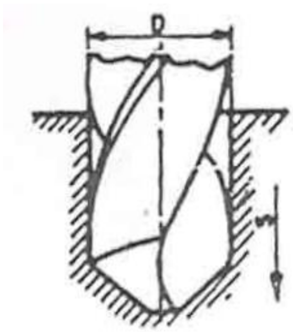

Figure 4. Cutting force during drilling operation [6]

Specification:

- Diameter of drill (D) : 32.5 mm
- Material to be cut : cast iron (200 BHN)
- Cutting speed (v) : 34.66 m/min
- Feed per revolution (s) : 0.3 mm/rev
- Efficiency of transmission : 85%

Cutting speed

$n = v \times 1000 / \pi . D$

$= 34.66 \times 1000 / \pi \times 32.5$

n = 339.5 rpm

Power at spindle

$N = 1.25 \times D^2 \times K \times n \times (0.056 + 1.5 \times S) \times 10^{-5}$

$= 1.25 \times (32.5)^2 \times 1.5 \times 339.5 \times (0.056 + 1.5 \times 0.3) \times 10^{-5}$

N = 3.4 KW

Where, K = material factor

$Th = 1.16 \times K \times D \times (100 \times S) \times 0.85$

$= 1.16 \times 1.5 \times 32.5 \times (100 \times 0.3) \times 0.85$

= 1018.6 kgf

Th = 10.186 KN

Torque at spindle

$Ts = 975 \times N / n$

$= 975 \times 3.4 / 339.5$

Ts = 2.269 kgf-m

B. Load Calculations and Constrains:

The cutting forces are not acting directly on the column but get transmitted through turret, X -slide and Z-slide. To calculate its effect moment from a point on column is taken.

Actual load on column:

a. Cutting force (Drilling thrust), w_1 = 10186 N (+Z direction) at a distance 791 mm in -Y direction and 592.58 mm in -X direction.

b. Weight of Turret, w_2= 1600 N (-Z direction) at a distance 634.73 mm in - Y direction and 303.72 mm in -X direction.

c. Weight of X-slide, w_3= 3018.75 N (-Z direction) at a distance 310.97 mm in - Y direction and 438.53 mm in - X direction.

d. Weight of Z-slide, w_4= 3871.19 N (-Z direction) at a distance 64.89 mm in - Y direction and 243 mm in -X direction.

Net load w in Z direction, at a distance ly in y direction and lx in x direction from a point of moment, has same effect of all the load listed above. Net load w is algebraic sum of all the load listed above.

C. Analysis Report:

Table .3 Analysis report for column: Drilling Operation

Particulars	Details
Model description	Column
Software used	ANSYS – Workbench 14.5
Assumptions	Only static loading is required. Self weight of structure is ignored.
Material to be used	FE 30, Material properties are as follows: E = 1.048 X10^5 MPa μ = Poisson's ratio = 0.25 ρ = Density = 7.19 X 10^{-9} tonne/mm3
Type of element used	Tetrahedral
Loads	Dead weight of Turret, X-slide, Z-slide. Thrust force during drilling.
Constraints	Column is fixed on base, so face from where column is assembled to base is taken fixed.
Constraints Parameter	Stress: 7.84532 -11.76798 M Pa and Deflection: 3 - 5 micron
Solution type	Standard design study, static analysis.

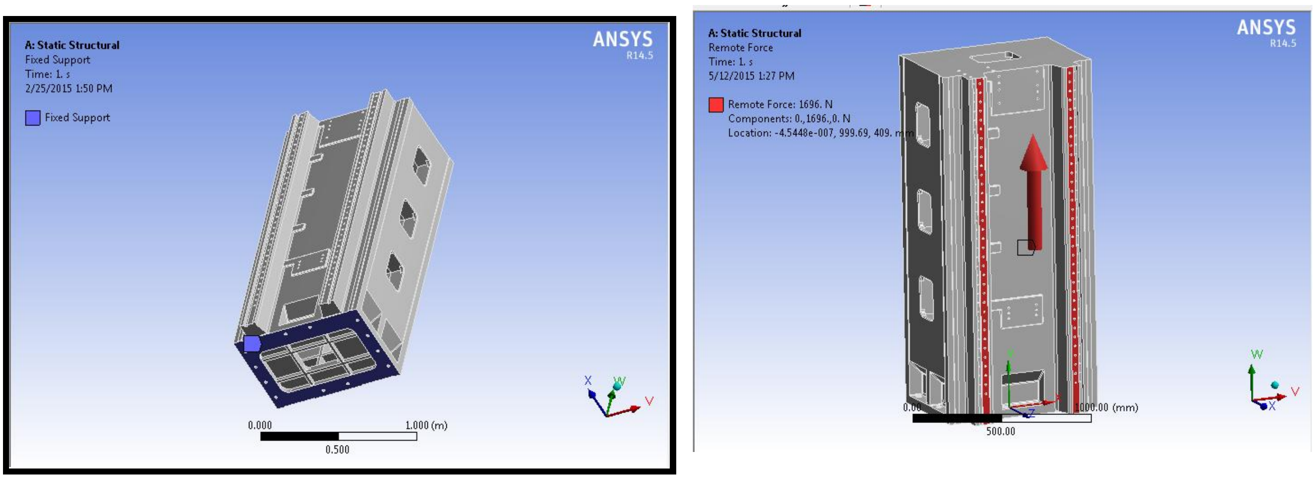

Figure 5. Constrain And Load on VTL Column

Table .4 FEA meshing details of column

Meshing Details	
Nodes	150400
Elements	89083
Element size	Default
Element type	Tetrahedral

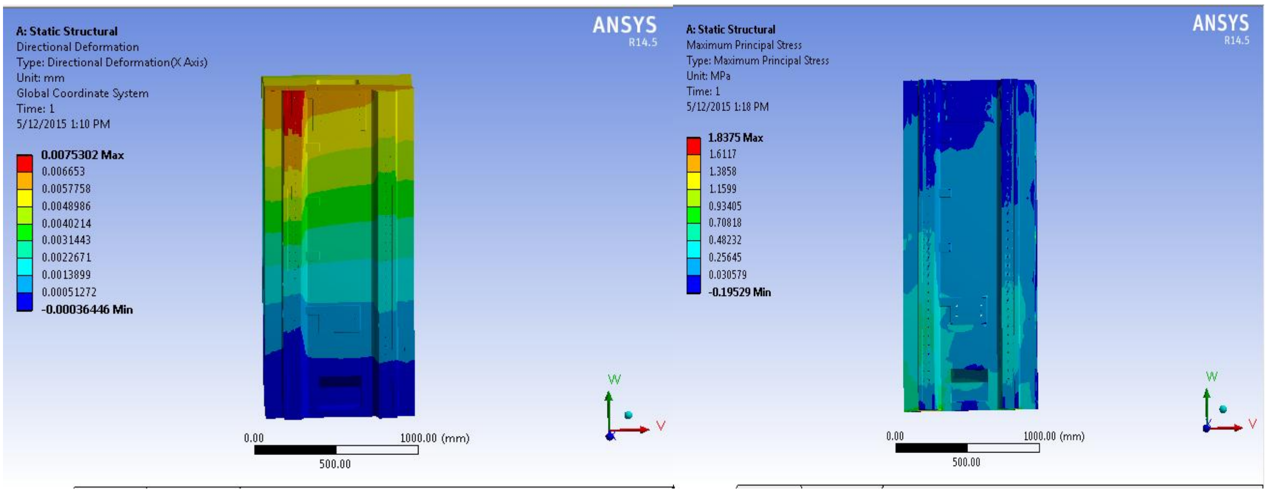

Figure 6. Analysis Simulation Results of VTL Column

Table .5 FEA Results of column

Part name	Parameter	Analyzed results obtained
Column	Maximum Deflection	0.0075302 mm
	Maximum Stress	1.8375 MPa

Maximum deflection value is 0.0075302 mm which is well within the specified limit of tolerable deflection (0.01mm). Maximum principal stress value is 1.8375 N/mm2 which is also satisfactory. Studying stress distribution result, it can be realized that except some Local portion of column, stress distribution is uniform and safe.

V OPTIMIZATION OF COLUMN STRUCTURE

Optimization of column structure is carried out by trial and error by consider the stiffness thickness as Variable parameter.

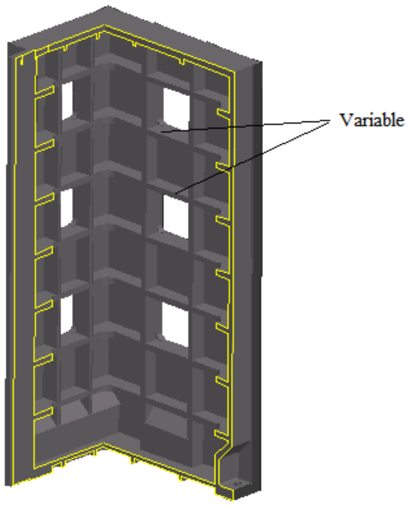

Figure 7.Column Model Showing Design Variable

Objective Function

1. To minimize Weight
2. To reduce cost

- The Stiffener thickness is Reduced in to the box type Column structure

- There are following reasons to Reduce thickness of stiffener to the box type Column structure
  - a) To reduces the overall weight of column structure
  - b) Easy to manufacture
  - c) During Analysis of column there are results less than the permissible limit.

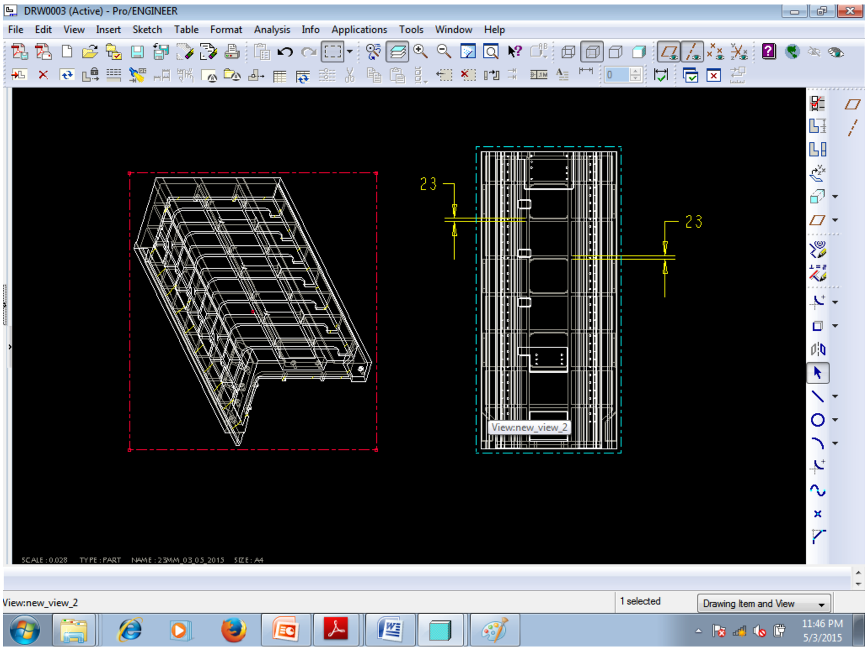

Figure 8. Design Modification for Optimization

Table .6 Optimization Results of column

Iteration No	Variable Thickness (in mm)	Weight Reduction (in Kg)	Deflection on column (in mm)
1	23	22	0.00748
2	21	43	0.00753
3	19	65	0.00758
4	17	86	0.00763
5	15	108	0.00893

VI CONCLUSION

- In the new economic year and globalization phase, industries are required to manufacture good quality machine tools with optimized performance at the moderate cost. From this work the following conclusions are made.
- The use of stiffeners can produce a great reduction in deformation of structure under the static loading.
- For cost reduction, mass can be reducing by use of stiffeners and apertures.
- The high transfer speed as well as the high cutting speed of machine tools is achieved by the structure design with less materials consumption.

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