ANALYSIS OF DYNAMIC AND FEM ON CNC-MACHINE TOOL COLUMN BY USING PRO/ENGINEER AND ANSYS SOFTWARE-2000

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***Abstract*— The increase of pace in the industrial and technological developments were become as phenomenal change in the trend of machine tool development that brings to the fore, the modern production requirements like higher speeds, closer tolerances and accuracy. Generally, the performance of a machine tool depends primarily upon the static and dynamic behavior of the basic structure. A computational procedure based on ANSYS-2000, a finite element package, for the dynamic analysis of a CNC machine tool column was developed, established and applied. The investigations have been carried out for varying aspect ratio, mesh size, modes of vibrations and column wall thickness covering a wide range of natural frequencies. In order to search for an optimum column, a number of affecting parameters have been identified and listed for further investigation. Column stiffness affects the dimensional accuracy of the work-pieces machined on a CNC machine tool. The static stiffness is characterized by column displacement whereas the dynamic stiffness is a function of the natural frequency of the column.**

***Keywords*— Dynamic, finite element column method, stiffness, Displacement.**

1. INTRODUCTION

There is a variety of applications of Computerized Numerically Controlled machine tools right from a drilling machine to a large gantry machining centre. Depending upon the application, the column might carry the spindle head only or both the spindle head and the knee-table unit. A column is an essential part of CNC drilling machines, vertical lathes, milling machines, boring machines, machining centers etc. High stiffness is the main requirement of columns. In order to achieve desired stiffness, one has to select the material, cross-section and many other parameters as discussed later here. Columns may have any of the following structures:

a. Welded steel structures
b. Cast structures
c. Combined welded and cast structures
d. Welded or cast structures of composite materials

1.1 COLUMN CROSS-SECTION

Depending upon stiffness requirement and the type of application, machine tool columns are made with varying cross-sections. The number and size of apertures are optimized along with the number and size of stiffeners. Hollow square boxes possess an efficient shape for engineering components due to their high inherent bending and torsional rigidities. For example, box-section steel girders are a familiar design of beams in bridges and other civil engineering structures. Currently, industrial interest exists in the use of tubes for the moving head of a milling machine. A box-type section has the highest torsional stiffness and it is best suited in terms of strength and stiffness. Hence, a square box-type section was selected for the column under consideration. The ratio of column height (1900 mm) to section width (700 mm) is about 2.71. Since the load is 3-dimensional, it is recommended to design and provide stiffeners to minimize warping of the column. Hence, the impact of stiffeners on column design has been studied thoroughly.

1.2 COLUMN STIFFNESS

Machine tools are characterized by high precision. This requires high structural stiffness. Static stiffness is defined as the ratio of the static force applied between cutting tool and work-piece, to the resulting static deflection. The stiffness requirement of Computerized Numerically Controlled (CNC) machine tools is quite high and is of the order of 150 N per micron. The design criteria for bending stiffness is that the maximum deflection of the structure in any plane must be less than or equal to the permissible deflection of the structure in the plane under consideration. The permissible deflection values are specified depending upon the desired accuracy of the machine tool. The maximum values are calculated by the finite element method. Similarly, the design criterion for torsional stiffness is that the maximum angle of twist per unit length of the structure must not exceed the permissible angle of twist per unit length of the structure. The permissible value of torsional stiffness for normal accuracy machine tools is 0.5 degrees per unit meter height of the column.

1.3 OBJECTIVE RESEARCH

- CNC machine column is selected for structural optimization.
- The main objective of this research is not only to develop an optimization criterion but also to optimize the column keeping in view the vital parameters such as column cross-section, wall thickness, stiffening rib dimensions, no. of vertical and horizontal.
- Column stiffness is used as the primary parameter to optimize and the finite element method is the technique used for analysis.

2. METHODOLOGY

A machine tool structure is composed of:

1. Columns for supporting Tools and other components
2. Beds to work as base
3. Guides for multi-directional movement
4. Headstock, Tailstock etc

Every component has its own role. It is not necessary to have all of these components. For example, vertical machine tools may not have beds. The structure must be stiff enough to sustain the cutting forces and other loads. Besides, a structure must not be bulky and hence expensive. In addition, the jobs produced on CNC machines are expected to be highly accurate. This has put rigid requirements on static stiffness and dynamic stability on CNC machine tools.

There are a number of methods to generate mesh for finite element analysis.

- By creating solid primitive elements such as cones, cylinders etc and performing Boolean operations on basic elements.
- Starting with wireframe profiles and generating an appropriate model by surface operations.
- Combining the above 2 methods.

One has to draw plan, elevation and side-view of each part. It is quite easy to draw but difficult to apply an accurate computational FEM for analysis.

Structural natural frequencies have many modes. The resonance may occur at any mode. Mostly, the resonance occurs at the first mode of vibration. An unstable machine tool structure will reduce its usability because of poor products. Unstability might give rise to many conditions such as:

- Sudden failure of the machine tool.
- Bent drive shaft.
- Foundation vibrations.
- Inaccurate work-pieces.
- High levels of noise.
- Random amplified peaks in spectrum.
- High level of friction between the tool and work-piece.

One need not consider all modes of vibration because not all modes of vibration affect product accuracy. Resonance is also linked to machine tool rpm. For most CNC machine tools, the minimum speed may be taken more than 100 rpm and the maximum less than 1000 rpm. For machine tools, most of the machining processes are repeated. It is desirable that the spindle speeds must be vibration-free, the friction between the tool and the job must be minimum and the foundation must be rigid. Resonance must be avoided.

2.1 MODAL ANALYSIS BY ANSYS

1. The material properties required for analysis (must be linear) should be specified as outlined in the analysis procedure.
2. The user may not be interested in all the modes of vibration. By default, it is the first six frequencies. However, one can specify any number of modes during computation.
3. The options are there to compute stress, strain and deformations along with modal shapes. It is up to the user. One gets what one wants.
4. The user can obtain the results in the form of bar charts, tabular format or any other graphical format. The results can be imported into Excel Worksheet and then further analyzed.
5. The results of the solution can be scaled by any random factor in order to view the results as per the requirement.
6. One can obtain the results of stress, strain, peak amplitude of vibration and deformation for:
   - Each mode.
   - Each frequency.

After preprocessing, FEA model is ready for solving. Figures 2.1 to 2.3 show steps of preprocessing of the column under consideration.

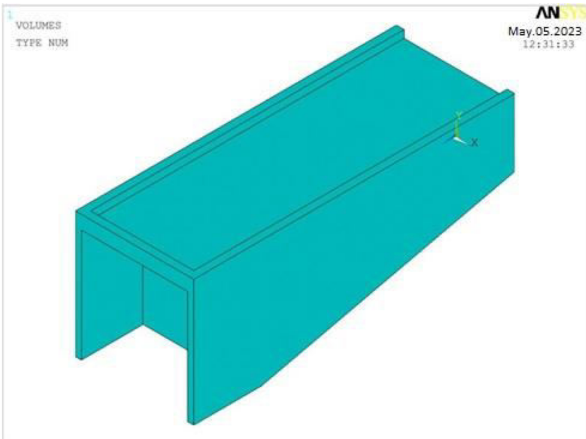

Fig. 2.1 Original Parametric model

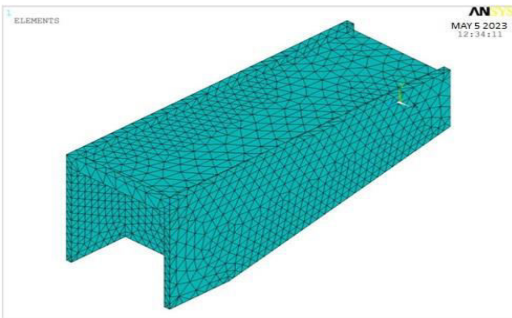

Fig. 2.2 Model with Finite Element Mesh

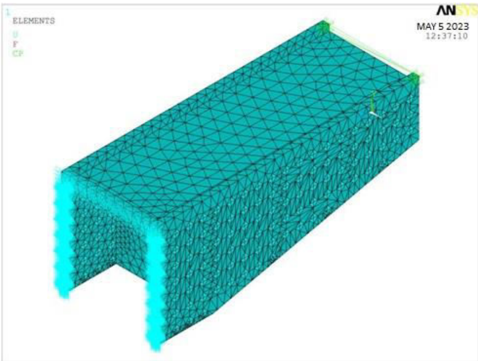

Fig. 2.3 FEM Model with Boundary Conditions and Loads

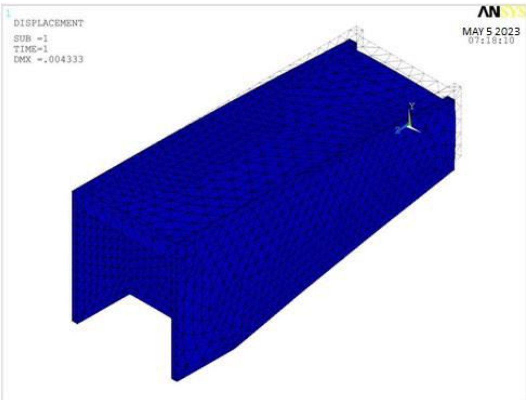

Fig. 2.4 Original and Compressed Column Structure after Processing

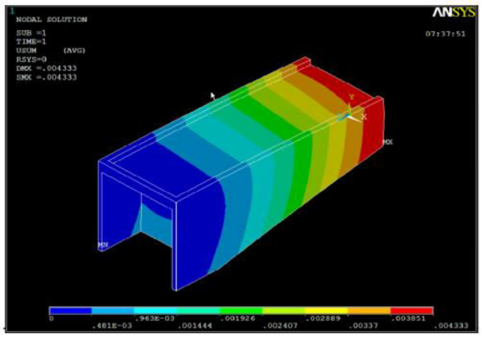

Fig. 2.5 Pattern of Displacement Vector Sum

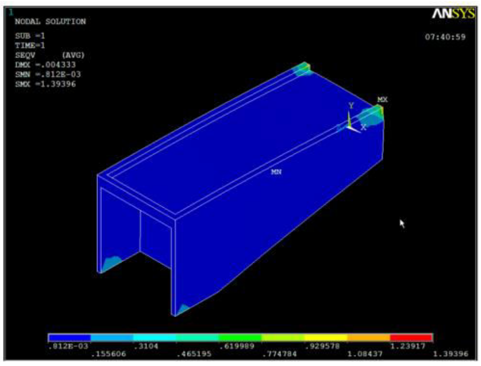

Fig. 2.6 Pattern of Von Mises Stress

3. SOFTWARE PACKAGES AND ALGORITHMIC LOGIC

3.1 PREPROCESSING PACKAGE PRO/ENGINEER 3-D

Pro/Engineer 3-D is the first successful parametric modeling software that can be used for everything from car bodies and aircraft engines to cellular phones and dollhouses to generate 3-D computer models. Following of its features that can be used for modeling are:

- A PRO/E model is an integration of blocks where each block can be edited individually.
- Each block may contain non-geometric data, for example fabricating processes and related expenses, and also information about location and relationships. This implies that blocks or elements do not require coordinate systems for placement, and they "know" how they are identified with remains of the model. Accordingly, changes are made rapidly and always correspond to the original design outline.
- PRO/E is a completely parametric CAD program. This implies the geometry of components (e.g., holes, slots) on a section must be completely specified as size, shape, area and location. This specification permits the user to write conditions which represent

- how contour on individual parts or various parts should correlate to identify with each other. For a designer, full parametric implies that one must have a procedure before one start modeling of what features one needs and how one wants to bound them inside the part
- Modules are connected together such that changes made in one module will be applied in other modules automatically. Pro/ENGINEER depends on a single data structure, with the capability to make improvement into the system. Therefore, when a change is made anywhere in the improvement process, it is propagated throughout the all design-through-manufacturing process.

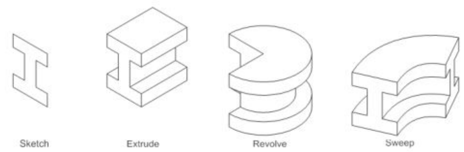

Fig. 3.1 Basic Functions in PRO/E for Creating Engineering Design

Fig. 3.2 Pattern Types in PRO/E

Table I. Maximum displacement, material volume and their Product P for different wall thicknesses

Wall Thickness t, mm	Displacement d, mm	Material Volume v, mm^3	Product P (d * v) mm^4
15	0.005501	87020250	478698
20	0.004251	112290250	477346
25	0.003537	137180250	485207
30	0.002915	161690250	471327
35	0.002443	185820250	453959
40	0.002211	208596000	461206
45	0.001979	232940250	460989

Table II. Maximum Displacement and Its First and Second Derivatives for DifferentWall Thicknesses

Wall Thickness, mm	Displacement, mm	Wall Thickness, mm	First Derivative of Displacement	Wall Thickness, mm	Second Derivative of Displacement
15	0.005501	17.5	-0.25	20	0.02144
20	0.004251	22.5	-0.1418	25	0.00386
25	0.003537	27.5	-0.1244	30	0.006
30	0.002915	32.5	-0.0944	35	0.0096
35	0.002443	37.5	-0.0464	40	1.67E-17
40	0.002211	42.5	-0.0464		
45	0.001979				

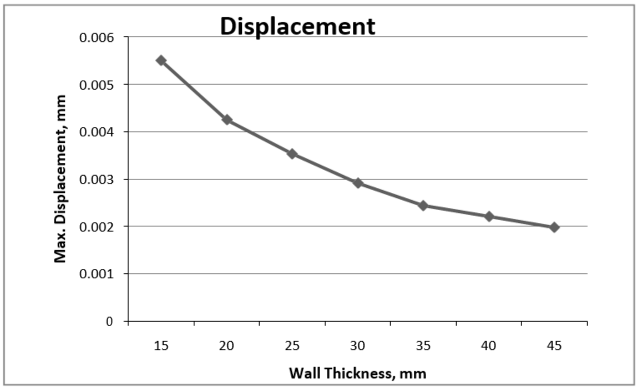

Fig. 3.2 Wall Thickness versus Maximum Displacement in mm

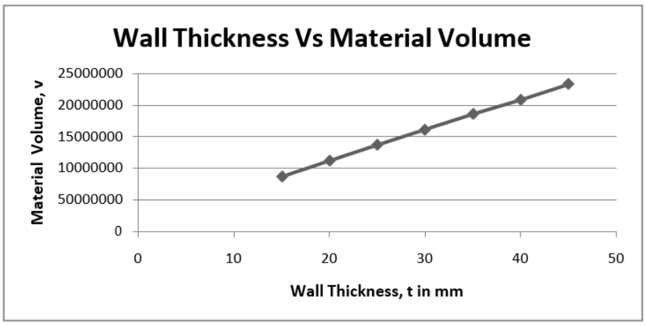

Fig. 3.3 Wall Thickness versus Column Material Volume

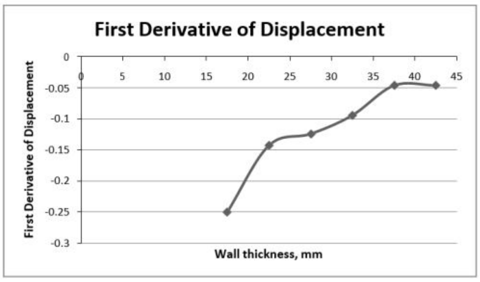

Fig. 3.4 Wall Thickness (mm) versus First Derivative of Displacement

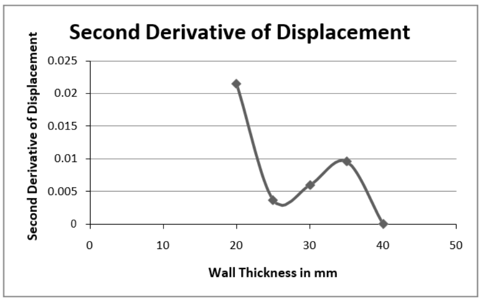

Fig. 3.5 Wall Thickness (mm) versus Second Derivative of Displacement

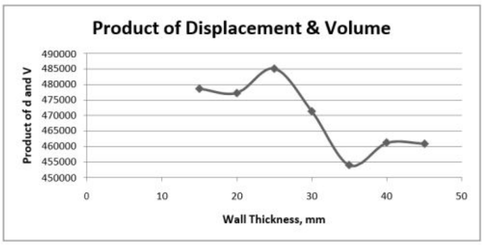

Fig. 3.6 Wall Thickness versus Product P of Displacement & Material Volume

ANSYS is broadly useful programming package (modular in structure) being used for simulation in structures, fluid dynamics, electromagnetism, physics, vibration and heat transfer for designers. Before the production of prototypes, it performs different tests at virtual platform. Moreover, 3D simulations at virtual platform also enable us to decide and enhance weak points, analyzing life and anticipating plausible issues. Besides, it can be integrated with other engineering CAD software packages. For example, CAD Data can directly be utilized by its "preprocessing" ability in building a geometry. For computation, finite element mesh can be created by this. We can get the output in form of numeric value and graphical presentation, subsequent to loading and analysis processes. Due to its different algorithm types, nonlinear material models and time based specific loading features, the advanced designing and engineering analyses created by ANSYS are quick, safe and practical in nature. Parametric CAD system and simulation technology are integrated in ANSYS. ANSYS through its solver algorithms, results into one of a kind performance and automation.

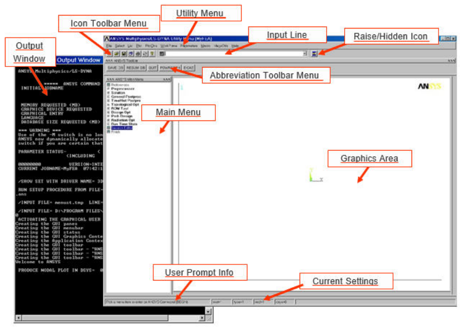

Fig. 3.7 GUI Layout in Ansys

4. RESULTS AND DISCUSSION

A column is a vital part of a machine tool as the column stiffness affects the dimensional accuracy of the work-pieces machined on a CNC machine tool. Thestatic stiffness is characterized by column displacement whereas the dynamic stiffness is a function of the natural frequency and the amplitude of vibration of the column. If the machine tool has a modal natural frequency close to the RPM of the rotor, its vibration level can be very high. Practically, for a column of high stiffness, the displacement should be as low as possible and the natural frequency should be far away from the operating speed zone of the machine tool providing a vibration-free environment. Besides, for a given displacement d, the material volume requirement, v for an optimal column must be minimum. Put together, the product P of displacement d and material volume v must be minimized in order to optimize a column. Hence, theminimum values of Product, P (d*v) as well as displacement, d have been used as the optimization criteria for column design. For dynamic stiffness, it is aimed to achieve the highest possible natural frequency coupled with minimum amplitude of vibration.

The column is made of Gray CI (ASTM 40). Its properties are given as under:

Modulus of Elasticity,	E	=	1.24e5 MPa (N/mm^2) = 124 GPa
Poisson's Ratio,	ν	=	0.25
Density		=	7200 kg/m^3
Tensile strength		=	276 MPa
Shear strength		=	400 MPa
Compressive yield strength		=	827 MPa
Hardness		=	180-302 Hb

Chemical Composition:

C	=	2.7-4%
Mn	=	0.80%
Si	=	1.8-3%
S	=	0.07% Max
P	=	0.2% Max
P	=	0.2% Max

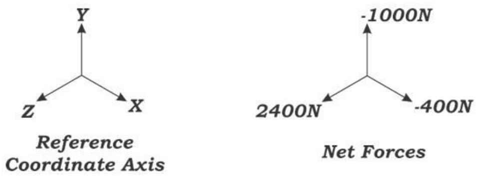

Fig. 4.1 Co-ordinate Axes and Forces Applied

For brittle materials, we use maximum normal stress criterion of failure. The 1st principal stress gives us the value of stress that is normal to the plane in which the shear stress is zero. The 1st principal stress helps us to understand the maximum tensile stress induced in the part due to the loading conditions.

4.1 DESIGN PARAMETERS:

The various design parameters used are:

1. Aspect ratio
2. Mesh Size
3. Modes of Vibration
4. Wall thickness of the column
5. Number of plain horizontal stiffening ribs
6. Cross-sectional Area(CSA) of plain horizontal stiffening ribs
7. Number of plain vertical stiffening ribs
8. Cross-sectional area of plain vertical stiffening ribs
9. Taper of side walls of a 3-sided column

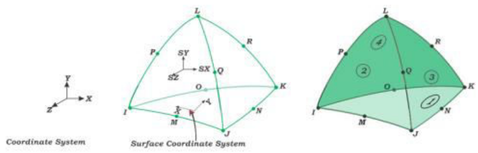

Fig. 4.2 SOLID 187 Geometry

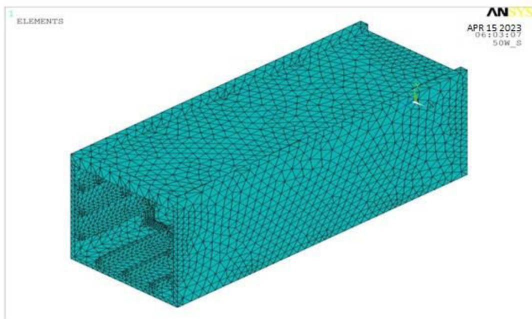

Fig. 4.3 A Typical Mesh

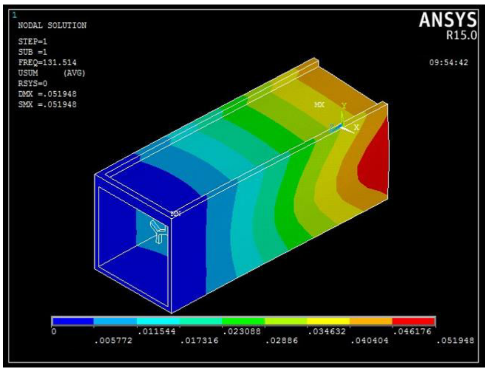

Fig. 4.4 Modal shapes of the column with 4 horizontal ribs having hexagonal openings

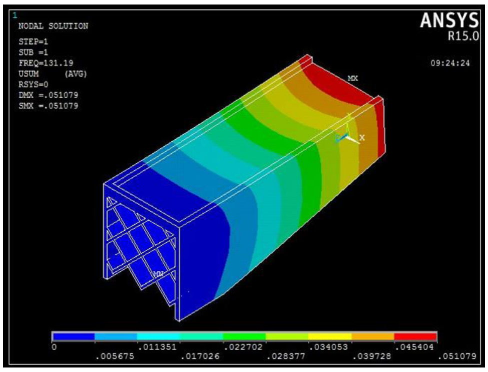

Fig. 4.5 Modal Shapes of a 3-Sided Column with Full-length ribs having 155 x 155mm Rotated Square Shaped Apertures

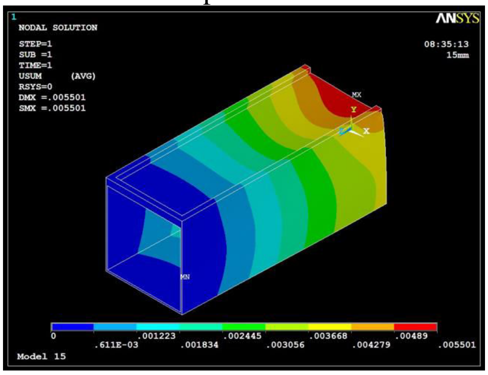

Fig. 4.6 Displacement vector sum for t = 15 mm

A machine tool acceptability largely depends on its static and dynamic characteristics. A column is an essential part of CNC machine tools. Depending upon the application, the column might carry the spindle head only or both the spindle head and the knee- table unit. The dynamic characteristics that affect product quality have to be investigated. These characteristics primarily include natural frequency, peak amplitude and the modes of vibration. Not all modes of machine tool structure affect product quality. As a result, only the modes that are excited during machining have to be taken into account.

The typical values of first natural frequency are 8.37 Hz for a column drilling machine, 11.23 Hz for a milling head, 12 Hz for a high speed micro lathe, 23 Hz for a machine tool structure, 36 Hz for a machine tool column and a vertical milling machine and 72 Hz for a machine spindle. On higher side, the values reported are 154 Hz for a CNC lathe bed, 230 Hz for a machine tool system, 256 Hz for a stiff machine spindle and 295 Hz for a tool holder assembly. Our investigations cover an extensive range of first natural frequency from 1.8 to 580 Hz. The aim is to design the CNC machine tool column with optimum mass location by investigating the impact of affecting parameters.

Table III. High Aspect Ratio versus Natural Frequency

Width X Height	Aspect Ratio	Theo. Freq.	$a_r * f_n$
10 X 1900	190	1.856821	352.8
25 X 1900	76	4.642054	352.8
50 X 1900	38	9.284107	352.8
100 X 1900	19	18.56821	352.8
150 X 1900	12.67	27.85232	352.8
200 X 1900	9.50	37.13643	352.8
300 X 1900	6.33	55.70464	352.8
400 X 1900	4.75	74.27286	352.8
500 X 1900	3.80	92.84107	352.8
600 X 1900	3.17	111.4093	352.8
700 X 1900	2.71	129.9775	352.8

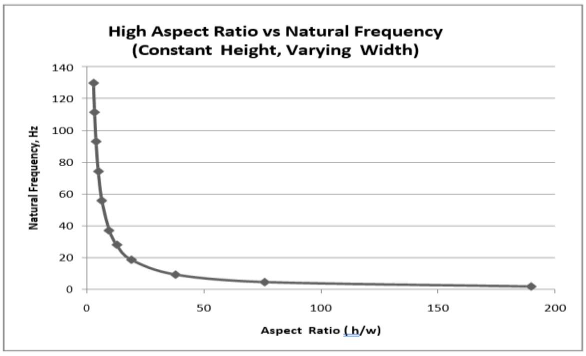

Fig. 4.7 High Aspect Ratio versus Natural Frequency

Table IV. Normal Aspect Ratio versus Natural Frequency

Width X Height	Aspect Ratio	Theo. Freq.	FEM Freq.	% Difference
700X1900	2.7	130	119.8	7.80106
700X2200	3.1	96.9	91.3	5.81
700X3500	5	38.3	37.4	2.79
700X4000	5.7	29.3	28.8	1.68873
700X5000	7.1	18.8	18.6	0.99249
700X6000	8.6	13	12.9	0.63641

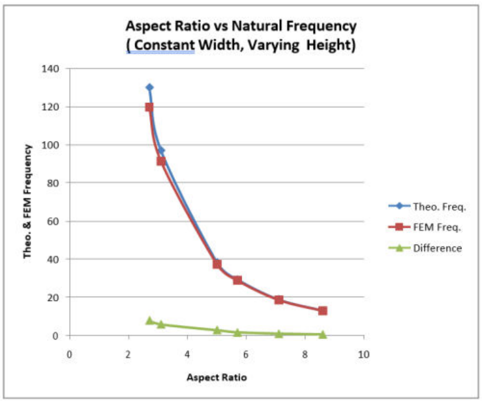

Fig. 4.9 Normal Aspect Ratio versus Natural Frequency

Table V. Low Aspect Ratio versus Natural Frequency

Width X Height	Aspect Ratio	Theo.Freq.	FEM Freq.	% Difference
700X900	1.3	579.3	432.5	25.3479
700X1100	1.6	387.8	290.9	24.9796
700X1400	2	239.4	207.6	13.2897
700X1650	2.36	172.3	155	10.059
700X1900	2.7	130	119.8	7.80106

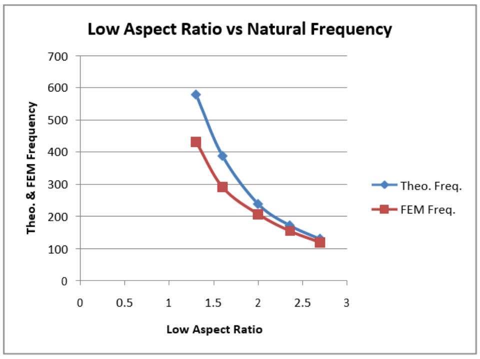

Fig. 4.10 Low Aspect Ratio versus Natural Frequency

Table VI. Mesh Size versus Natural Frequency

Aspect Ratio	Mesh Type	Theo. Freq.	FEM Freq.	% Difference
2.7	Normal	130	119.8	7.80106
2.7	Fine	130	119.8	7.80106
2.7	Super Fine	130	119.7	7.80106

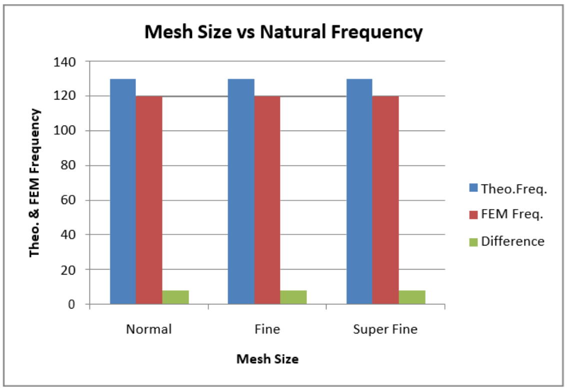

Fig. 4.11 Mesh Size versus Natural Frequency

Table VII. Wall Thickness vs First Natural Frequency

Wall Thickness. Mm	Natural Frequency, Hz	Increase in Frequency per unit thickness
15	73.9	-
25	117.9	4.4
35	132.6	1.47
45	135.3	0.26

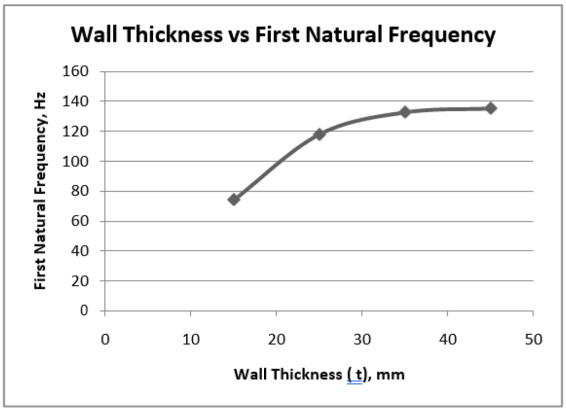

Fig. 4.12 Wall Thickness vs First Natural Frequency

5. CONCLUSIONS

- The dynamic analysis by FEM (using ANSYS) for the values of aspect ratio, a_r greater than 2.7 is reasonably accurate, With refined mesh size, there is no change in frequency computation.
- Hence, the normal mesh used for present investigations is good enough.

- For the first 3 modes, the maximum error is about 4%. For the modes from 4 to 9, the maximum error is about 2.25%. These findings suggest that the finite element method based on ANSYS is reliable for performing the dynamic analysis for all modes of vibration for CNC machine tool column.
- Our investigations cover an extensive range of first natural frequency from 1.8 to 580 Hz. A rigid structure with low mass which has been properly distributed results into higher natural frequency
- From 15 to 35 mm, as the thickness is increased the frequency also increases appreciably. After 35 mm, the curve becomes almost flat. Hence, for the column under consideration 35 mm may be taken as optimum thickness.
- This happens to be the optimum thickness from deflection point of view also. The optimum column thickness is less than 2% of the height and not more than 5% of the width of the square hollow column. This may serve as a guideline for column design.
- The product P increases dramatically as CSR of vertical ribs is increased indicating that the impact of plain vertical ribs of increased cross-section on static stiffness of the column is negative from material saving point of view.
- Dynamically, there is a marginal decrease in the amplitude of vibration with an increase in CSA (Cross- section Area) of vertical ribs.
- A 400% increase in CSA results into about 4.4% decrease in the amplitude of vibration. Besides, the natural frequency remains almost constant as the CSA of vertical ribs is increased from 200 to 1000 mm^2.
- Thus, dynamically it is immaterial whether the designer uses vertical stiffening ribs or not. Finally, overall design considerations recommend no vertical stiffening ribs for a CNC machine tool column.
- An increase in taper angle results into about doubling the natural frequency and almost constant amplitude of vibration.
- Hence, for better vibration characteristics required for high speed machine tools, it may be recommended to use a 3-sided column with tapered side walls having taper angle of about 14 degrees.
- As per the static analysis results (for a column of wall thickness 25 mm), an increase in taper angle from 1.5 to 14.7 degrees results into about 80% increase in displacement and a 40% increase in the product P of d and v whereas the material volume requirement is decreased by about 20% only.
- These results indicate that with higher taper angles, the rate of increase of displacement as well as product P (d * v) is also quite high leading to an inference that for high static stiffness required for rigid machine tools, a 3-sided column without tapered side walls is a better choice.

Scope of Further Work

a. The finite element method provides an approximate solution for good mesh has been used.
b. The stiffening ribs with more bionic shapes can be explored further.
c. The welded structures as well as composite materials offer a new dimension of research as

machine tool parameters.

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