

Effect of Stiffening Ribs on the Dynamic and Static Stiffness of a Computerized Numerically Controlled Machine Tool Column

Arun Kumar Arya
Research Scholar,
Mechanical Engineering,
NIMS University,
Jaipur-303121, India

Dhananjay Gupta
Arya College of Engineering & IT,
Delhi Road,
Kukas, Jaipur-302028, India

Abstract

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. A computational procedure based on ANSYS, a finite element package, for the static and dynamic analysis of a CNC machine tool column was applied [1, 2]. Derived parameter method [1] developed by the authors was used for mathematical modelling.

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. 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, the minimum 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.

The impact of the number and cross-sectional area of horizontal as well as vertical stiffening ribs on column displacement and its natural frequency was studied. The results obtained and the conclusions derived have been reported in the paper.

Keywords-Displacement, finite element, column, stiffness, ribs

I. INTRODUCTION

A computational procedure based on ANSYS, a finite element package, for the static and dynamic analysis of a CNC machine tool column was developed, established and applied [2]. The product accuracy is a function of displacement and the vibration characteristics of machine tool structure. Low displacement and vibration-less environment require high column stiffness.

An optimum design of machine-tool structures requires consideration of a number of machining parameters including nature of the forces involved. Recently, researches have been reported in the field of structural design of machine tools for improving stiffness and reducing cost[3]-[5].

Hollow square boxes possess an efficient shape for engineering components due to their high inherent bending and torsional rigidities[6]. The column is a vital part affecting the stiffness of a machine tool. The column stiffness is primarily controlled by its size, shape and material. However, a lot of parameters such as shape of the column, column height, cross-section, wall thickness, stiffening rib dimensions, no. of vertical and horizontal ribs, no. of apertures, types of apertures, angle of taper, bionic design aspects etc need to be considered for an optimal design. An optimal thickness for the column under consideration has already been established [2]. This paper focuses on the role of stiffening ribs in the design of a CNC machine tool column. A number of parameters of stiffening ribs are analysed and discussed.

II. DESIGN SPECIFICATIONS

A CNC machine column of Gray CI (ASTM40) was taken for design. The column 3-D view is shown in Fig. 1. A hollow column of cross-section 700 mm by 700 mm and of height 1900 mm was taken. The wall thickness, t was confined to 25 and 35 mm [1] for the purpose of analysis.

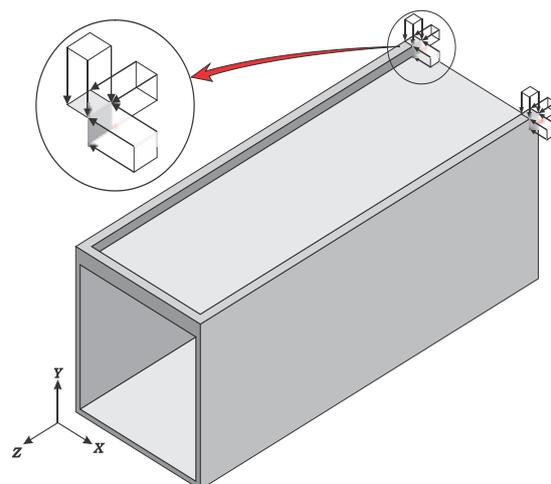


Fig. 1: CNC Machine Column (3-D View)

The net forces applied [7]-[9] are given in Fig. 2. The three components of forces are -400 N, -1000 N and 2400 N along X, Y and Z axes respectively. The bottom surface of the column was

constrained for all 6 degrees of freedom. No other boundary condition was applied.

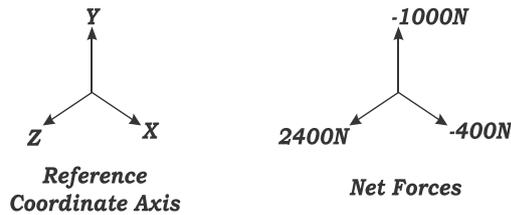


Fig. 2: Co-ordinate Axes and Forces Applied.

III. DESIGN OPTIMIZATION

For an acceptable accuracy of machined work-pieces, a machine tool should be statically as well as dynamically stable. For optimal design of a machine tool structure, it is imperative that the vital components of a machine tool should satisfy the following criteria:

- The displacement, d should be as low as possible [10].
- The material volume requirement, v should be minimum.
- The natural frequency should be the highest possible assuming that most machining operations have a low range of the frequency of oscillation.

For analysing the effect of stiffening ribs on stiffness, the above listed optimization criteria have been used.

IV. FINITE ELEMENT ANALYSIS

PRO-ENGINEER 3D product development software was used for mesh generation. A 3-dimensional 10-node tetrahedral structural element (SOLID187 as per ANSYS) was used. SOLID187[11] has a quadratic displacement behaviour and is well suited to modelling irregular meshes.

The finite element analysis for the column was done using ANSYS software package. Typical values of the no. of nodes and equations are: number of super nodes = 4207; number of compressed nodes = 45200 and number of equations = 135600.

The basic outputs obtained are: Displacements in x , y and z directions, displacement vector sum, product (P) of displacement (d) and material volume (v), natural frequency and the material volume requirement.

V. RESULTS AND DISCUSSION

The various parameters considered are as under:

- Number and cross-sectional area of horizontal stiffening ribs for a 4-sided column.
- Number and cross-sectional area of vertical stiffening ribs for a 4-sided column.

1. Number of Horizontal Stiffening Ribs

For analysis, equi-spaced horizontal stiffening ribs were attached to the column. The number of horizontal ribs (NHR) was varied from 2 to 7 with an increment of 1. A 3-dimensional view with 4 ribs is shown in Fig. 3.

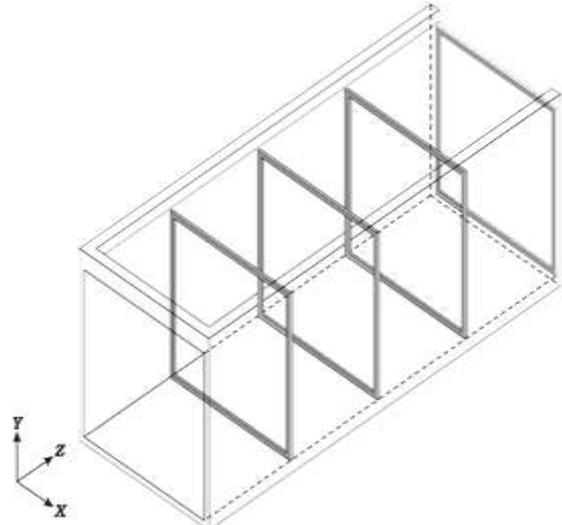


Fig. 3: A 3-D View of 35 mm Wall Thickness Column with 4 Equi-spaced Stiffening Horizontal Ribs(20x20 mm)

The Table 1 contains the computed values of displacement (d), material volume (v), product (P) and the natural frequency (f) for varying no. of horizontal ribs (NHR). Here, wall thickness, $t = 35$ mm and rib area = 20 mm x 10 mm.

TABLE 1. COMPUTED VALUES OF d , P AND f AGAINST NHR.

NHR	$P = d \times v$ (mm^4)	d (mm)	Volume, v (mm^3)	Natural Frequency (Hz), f
0	1.271e7	0.068404	185820250	132.65
2	1.2219e7	0.065583	186316250	130.25
3	1.21778e7	0.065274	186564250	130.22
4	1.2171e7	0.06515	186812250	130.20
5	1.21456e7	0.064929	187060250	130.23
6	1.21323e7	0.064772	187308250	130.20
7	1.21266e7	0.064656	187556250	130.15

The graphical plots for d , P and f against NHR are exhibited in Figs. 4, 5 and 6 respectively.

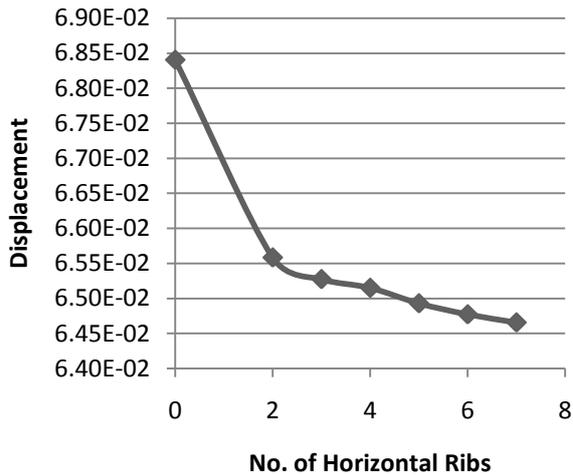


Fig. 4: No. of Horizontal Ribs vs Maximum Displacement

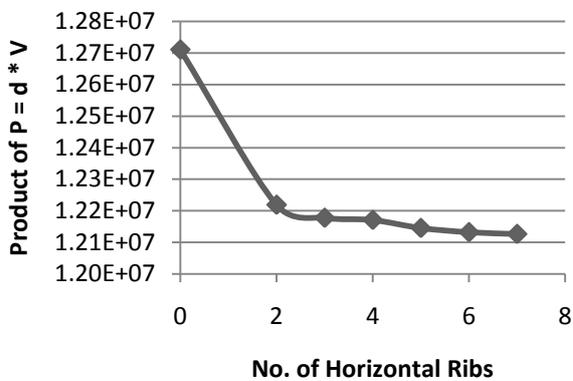


Fig. 5: No. of Horizontal Ribs versus Product P(d * v)

From Fig. 4, as the no. of horizontal ribs is increased from 2 to 7, the displacement decreases, but the rate of decrease of displacement also decreases. This means that the impact of NHR on displacement is gradually diminished. This fact is further demonstrated by Fig. 5 where after NHR = 5, the decrease in product P is negligible.

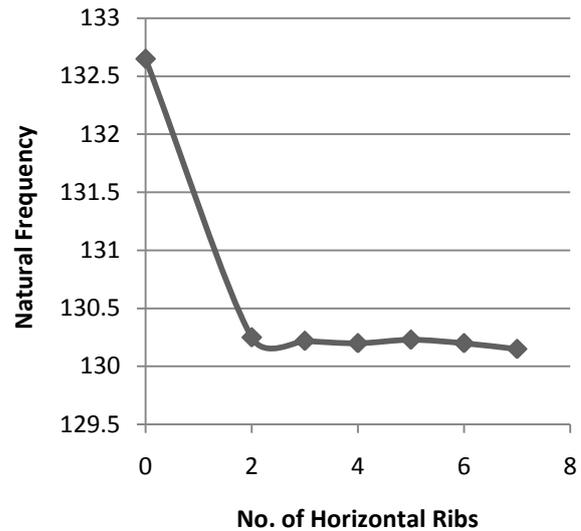


Fig. 6: No. of Horizontal Ribs versus Natural Frequency, f.

From Fig. 6, the natural frequency remains almost constant with an increase in NHR from 2 to 7. Hence, dynamically, NHR has no impact on column stiffness. Statically, 5 is the desirable NHR for the given column which may serve as a guide line for designing CNC machine columns. Dynamically, even a lower value of NHR is good enough.

2. Cross-sectional Area (CSA) of Horizontal Stiffening Ribs

In section V.1, study on the impact of the number of horizontal stiffening ribs on displacement was done by keeping the cross-section area of the ribs constant equal to 200 mm². This study was extended further by varying the area of cross-section from 400 (20 x 20) to 4225 (65 x 65) mm² and keeping the number of ribs equal to 4 with optimum column wall thickness of 35 mm. The rib width was kept equal to rib thickness.

TABLE 2. COMPUTED VALUES OF d, P AND f AGAINST CSA OF HORIZONTAL STIFFENING RIBS.

CSA (Ribs) (mm ²)	P = d x v (mm ⁴)	Volume, v (mm ³)	Natural Frequency (Hz), f	d (mm)
400 (20 x 20)	1.18251e7	189724250	133.69	0.062328
625 (25 x 25)	1.12774e7	191870250	133.59	0.058776
1225 (35x35)	1.056e7	197482250	132.79	0.053472
2500 (50x50)	1.0201e7	209020250	130.04	0.048804
4225 (65x65)	1.0231e7	224014250	125.93	0.04567

The Table 2 contains the computed values of displacement (d), material volume (v), product (P) and the natural frequency (f) for different areas of rib cross-section varying from 400 (20 x 20) to 4225 (65 x 65) mm².

The graphical plots for d, P and f against different areas of cross-section of horizontal ribs are displayed in Figs. 7, 8 and 9 respectively.

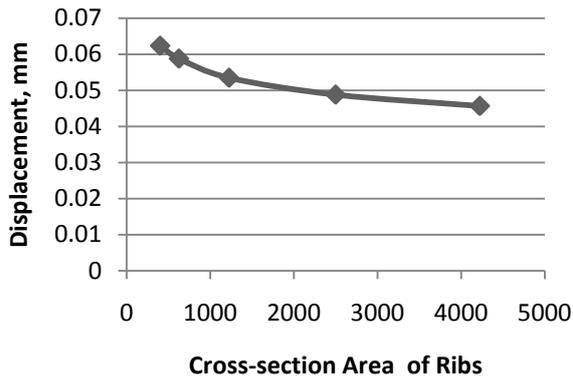


Fig. 7: Cross-section Area of Horizontal Ribs versus Maximum Displacement.

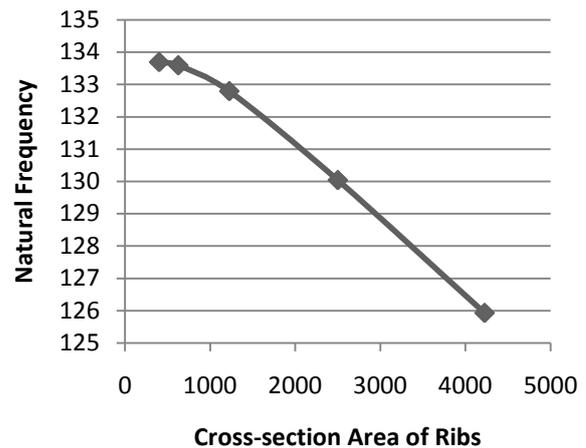


Fig. 9: Cross-section Area of Horizontal Ribs versus Natural Frequency.

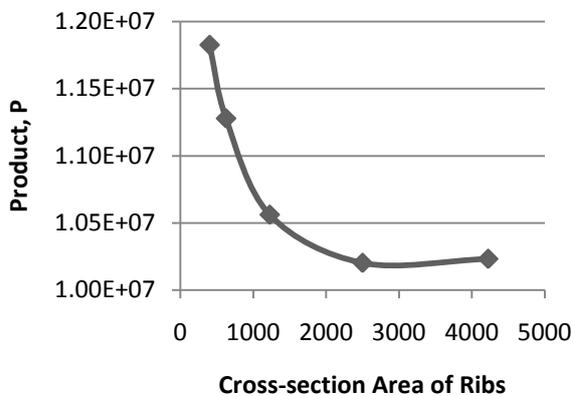


Fig. 8: Cross-section Area of Horizontal Ribs versus Product, P

As per Fig. 7, with an increase in the cross-section area of horizontal stiffening ribs, the displacement is obviously decreased. But the rate of decrease of displacement per unit increase of cross-section area of ribs is maximum at $CSA = 1225 \text{ mm}^2$ corresponding to the rib thickness equal to 35 mm which is equal to the column thickness (35 mm). This fact is further demonstrated by Fig. 8 where for $CSA > 1225 \text{ mm}^2$ corresponding to the rib thickness equal to 35 mm, the product P almost flattens out.

Dynamically, the natural frequency remains almost constant up to $CSA = 1225 \text{ mm}^2$ (Fig. 9) and after this value, the rate of decrease in f increases. Thus, for efficient design based on dynamic as well as static considerations, the thickness of horizontal ribs should be equal to the optimum column thickness. It may not be more than the column thickness. For our analysis, the width of horizontal ribs has been taken equal to its thickness.

3. Number of Vertical Stiffening Ribs

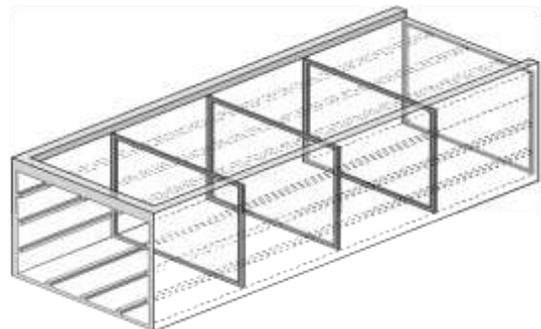


Fig. 10: A 3-D View of the 4-sided Column (wall thickness = 35 mm) with 4 Horizontal and 3 Vertical Ribs.

After optimizing for horizontal ribs, it is logical to analyse the impact of vertical ribs also on design parameters. The no. of vertical ribs (NVR) were varied from 1 to 3 with an increment of 1. A 3-dimensional view of the column with 4 horizontal and 3 vertical ribs is shown in Fig. 10.

The Table 3 contains the computed values of displacement (d), material volume (v), product (P) and the natural frequency (f) for varying no. of vertical ribs (NVR). Here, wall thickness, $t = 35 \text{ mm}$ and rib area = 20 mm x 10 mm.

TABLE 3. COMPUTED VALUES OF d, P AND f AGAINST NVR.

NVR	P = d x v (mm ⁴)	Volume, v (mm ³)	Natural Frequency, Hz	d (mm)
0	1.271e7	185820250	132.65	0.068404
1	1.2223e7	187580250	129.88	0.065163
2	1.2266e7	189092250	129.862	0.06487
3	1.2322e7	190604250	129.62	0.064647

The computed values of d, P and f against the no. of vertical ribs are plotted in Figs. 11, 12 and 13 respectively.

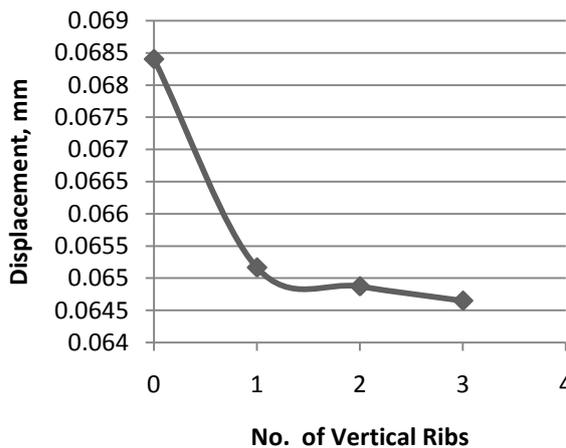


Fig. 11: No. of Vertical Ribs Vs Maximum Displacement

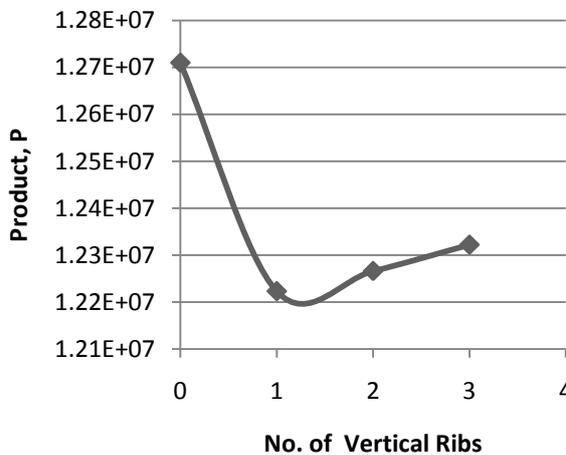


Fig. 12: No. of Vertical Ribs versus Product P(d * v)

From Fig. 11, there is hardly any decrease in displacement with an increase in the no. of vertical ribs from 1 to 3. From Fig. 12, the product P (v * d) increases as NVR is increased from 1 to 3 indicating that the plain vertical ribs of small cross-section have hardly any impact on static stiffness of the column.

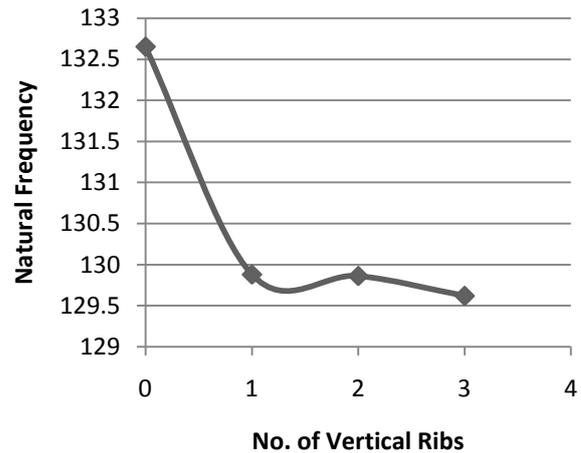


Fig. 13: No. of Vertical Ribs versus Natural Frequency, f.

Dynamically, the natural frequency, rather, decreases marginally as NVR is increased from 0 to 1 (Fig. 13) and further increase in NVR has practically no impact on f. Thus, based on static as well as dynamic considerations, vertical ribs of small cross-section are redundant from design point of view.

4. Cross-section Area(CSA) of Vertical Ribs

As observed earlier, the vertical ribs of small cross-section have hardly any impact on column stiffness. The pertinent question is “Does the cross-section of vertical ribs have any impact on column stiffness?” In order to find an answer, the cross-section of vertical ribs was varied from 200 mm² to 1000 mm². Here, NVR =3, wall thickness = 35 mm.

TABLE 4. COMPUTED VALUES OF d, P AND f AGAINST CSA OF VERTICAL STIFFENING RIBS.

CSA (Ribs) (mm ²)	P = d x v (mm ⁴)	Volume, v (mm ³)	Natural Frequency, Hz	d (mm)
200	1.2322e7	190604250	129.62	0.064647
600	1.2794e7	199712250	129.36	0.06406
800	1.284e7	204260250	128.97	0.062861
1000	1.2905e7	208808250	128.59	0.061804

The Table 4 contains the computed values of displacement (d), material volume (v), product (P) and the natural frequency (f) for different areas of rib cross-section (of vertical ribs) varying from 200 to 1000 mm².

The graphical plots for d, P and f against different areas of cross-section of vertical ribs are exhibited in Figs. 14, 15 and 16 respectively.

As seen from Fig. 14, there is a marginal decrease in displacement with an increase in CSA (Cross-section Area) of vertical ribs. A 400% increase in CSA results into about 4.4 % decrease in displacement. The question still remains “Is it worth from material volume point of view?” As displayed in Fig. 15, the product P (v * d) increases dramatically as CSA of vertical ribs is increased indicating that the

impact of plain vertical ribs of any cross-section on static stiffness of the column is not worth consideration from material saving point of view.

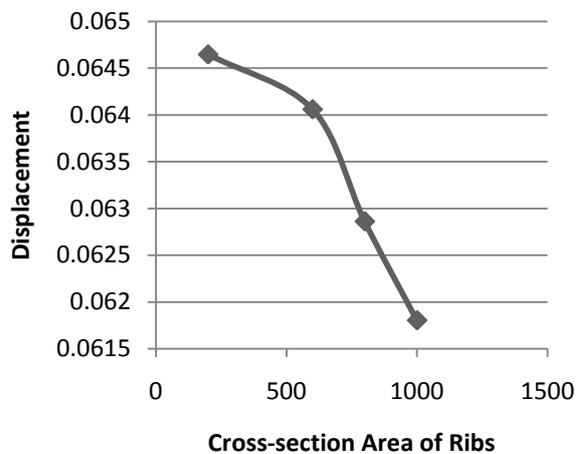


Fig. 14: CSA of Vertical Ribs vs Maximum Displacement

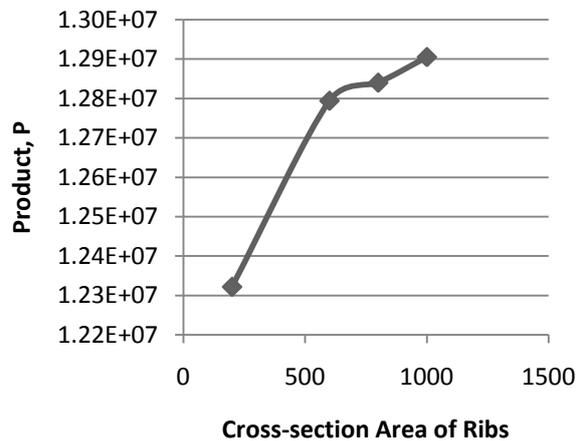


Fig. 15: CSA of Vertical Ribs versus Product P(d * v)

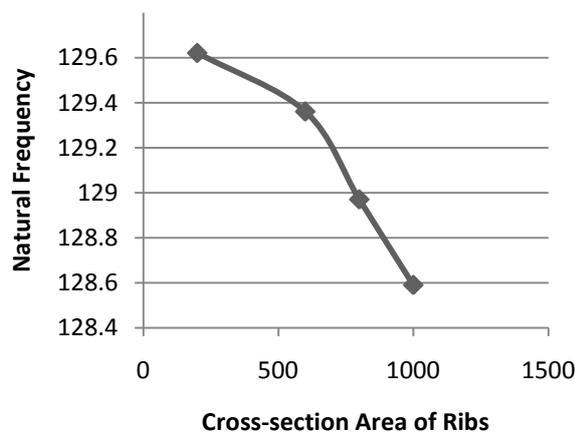


Fig. 16: Cross-section Area of Vertical Ribs versus Natural Frequency.

Dynamically, the natural frequency remains almost constant as the CSA of vertical ribs is increased from 200 to 1000 mm² (Fig. 16). 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.

VI. CONCLUSIONS

The impact of horizontal and vertical stiffening ribs on column design may, now, be summarized as under:

For a CNC machine column of good length, 5 is the optimum number of horizontal ribs which may serve as a guide line for column design. Dynamically, even a lower value of NHR is good enough.

The thickness of horizontal ribs should be equal to the optimum column thickness. For the sake of efficiency, it may not be more than the column thickness. The width of horizontal ribs may be taken equal to its thickness.

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.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contribution of Mr. Anurag Agrawal, Chairman, Arya College of Engineering & IT for providing us the facilities to carry out the computational work at the research cell of the college. We further acknowledge the technical support provided by Mrs. Swati Gupta, Director, COMPRO, Mansarovar, Jaipur.

REFERENCES

- [1] Manu Gupta and P. D. Murarka, "Optimization criteria for the design of a computerized numerically controlled machine column using finite element method", *International Journal of Mechanical Engineering*, Vol. 41, Issue 2, pp. 1180-1184, September, 2013.
- [2] Arun Kumar Arya, Manu Gupta and Dhananjay Gupta, "Dynamic Analysis of a Computerized Numerically Controlled Machine Tool Column", *International Journal of Mechanical Engineering*, Vol. 42, Issue 2, pp. 1263-1268, December, 2014.
- [3] Dezhong Kong, Jingfeng Shen & Baohui Li; "Finite-element Analysis and Optimization for the Column of Numerically Controlled Triaxial Deep Hole Drilling Machine", *Mechanical Engineering Research*; Vol. 2, No. 1; 2012.
- [4] Yuhong Zhang, Wenhua Ye, Sheng Leng & Wenyong Shan; "Bionic Design for Column of Gantry Machining Center Using Honeycomb Structures", *Proceedings of the World Congress on Engineering 2012*, Vol III, WCE 2012, July 4 - 6, 2012, London, U.K.
- [5] L. Zhao, W.Y. Chen & J.F. Ma, "Lightweight Design of High-speed Working Table Based on Structural Bionic", *Modular Machine Tool & Automatic Manufacturing Technique*, no.1, pp.1-4, 2008.

- [6] Wedad I. Alazzawy, “Static and Dynamic Analysis of Stiffened Plate Used in Machine Tool Column”, *Journal of Engineering*, Vol. 14, No 4, December 2008.
- [7] Hedi Yangui et al, “Influence of Cutting and Geometrical Parameters on the Cutting Force in Milling”, *Engineering, Scientific Research*, 2010, 2, 751-761.
- [8] Joshi, A.M. et al, “Finite Element Analysis of CNC Lathe Headstock”, *Journal of Information, Knowledge and Research in Mechanical Engineering*, Vol. 2, No. 1, Page 135, Oct. 2012.
- [9] Edmund Isakov, “Understanding tangential cutting force when milling”, *Cutting Tool Engineering Plus*, May 2012 / Volume 64 / Issue 5.
- [10] Georgi STOYCHEV, “FE Analysis of Gray Cast Iron Structural Elements”, *Machine Design*, May 10, 2010.
- [11] Release 11.0 Documentation for ANSYS, www.ansys.com