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DYNAMIC ANALYSIS AND COMPARISON OF DIFFERENT DESIGNS OF MILLING MACHINE BEDS MADE OF MINERAL CASTING

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Abstract: *Machine-tools represent a fundamental area of interest in engineering. More and more machine-tool builders have started to use composite materials, with an emphasis on a class of polymer concrete called mineral casting that is used in producing structural components such as beds, columns, tables, portals etc. The paper presents a simplified three axes milling machine bed designed by the author and a series of numerical analyses which simulate the behavior of the component when subjected to the vibrations caused by the machining process. Four different versions of bed designs are studied in order to assess several common shapes. Ribbing comes out as a good compromise between cost and performance, both being important metrics.*
Keywords: *composite material machine-tools, mineral casting bed, vibration analysis.*

1. INTRODUCTION

Machine-tools represent a fundamental area of interest in engineering. They are important in all stages of manufacturing starting with fabrication preparation all the way to finishing products.

More and more machine-tool builders have started to use composite materials, with an emphasis on a class of polymer concrete called mineral casting that is used in producing structural components such as beds, columns, tables, portals etc. This material has a very good price-performance ratio and only requires a minimum of equipment and unqualified workers. It also has a number of benefits besides the economical ones: mineral casting is extremely versatile, it can hold tight tolerances straight from casting and it can have other components such as cooling pipes inserted during casting.

Some of its greatest advantages are its low mass and high vibration damping capacity. The present paper aims to research how the shape of a milling machine bed made of this material influences the machine's damping and lessens the effects of resonance.

The author has designed a simplified CAD model of a 3 axes milling machine bed in order to achieve this goal. The component was dimensioned based on the loads calculated using Kennametal's calculator for end-milling applications and on existing machine-tools. A hypothetical scenario was created that features an intense milling process: a high-performance carbide end mill with a diameter of 20 mm and 3 teeth cuts hardened steel. The data are presented in table 1. As an observation, the tensile strength of the material is automatically determined based on the Rockwell hardness.

Table 1
Input data for Kennametals's calculator

End mill	
Diameter (d) [mm]	20
No. of teeth (z) []	3
Material	
Rockwell hardness [HRC]	65
Brinell hardness [HB]	739
Tensile strength [MPa]	2548
Cutting parameters	
Cutting speed (v_c) [m/min]	150
Depth of cut (a_p) [mm]	1
Width of cut (a_e) [mm]	20
Feed per tooth (f_z) [mm]	0.1
Machine efficiency (E) []	0.9

Table 2

Table 2. Data Calculated Using Kennametals' App

Parameter	**Result**
Spindle speed (n) [min^{-1}]	2387.3
Feed (vf) [mm/min]	716.2
Metal removal rate Q [cm^3/min]	143.24
Tangential cutting force (F_t) [N]	1142.778
Torque at the cutter (M) [Nm]	11.43
Power at the cutter (P_s) [kW]	4.55
Power at the motor (P_m) [kW]	5.06

2. SIMPLIFIED CAD MODEL OF THE MACHINE BED

The bed's dimensions have been chosen in accordance to the size of a small milling machine. The machine is a standard 3 axes vertical one with the horizontal X and Y axes mounted on top of one another and the Z axis (spindle axis) mounted on the column. It features a large width of 500 mm in order to provide strength and stiffness to the X and Y axes sitting on top of it.

The bed is designed so as to be cast as a single part in an upside down position. This is done so as to ensure more compact surfaces where the linear guides and ballscrews are attached.

The horizontal hole with a diameter of 80 mm cuts through the entire column and is designed so as to allow mounting of the motor on the back of the machine and connecting it to the horizontal front to back ball screw (Y axis).
Even though the outer shape of the component is the same for all the models, the core part varies from an empty shell to two ribbed versions to a full casting without any empty spaces. The author has chosen a minimum wall thickness of 40mm and this means that a maximum aggregate size of 40/5=8mm can be used. The part also doesn't feature any reinforcement such as chopped fibers or steel rebar in order for it to have isotropic properties and to lower the cost of materials and especially labor.

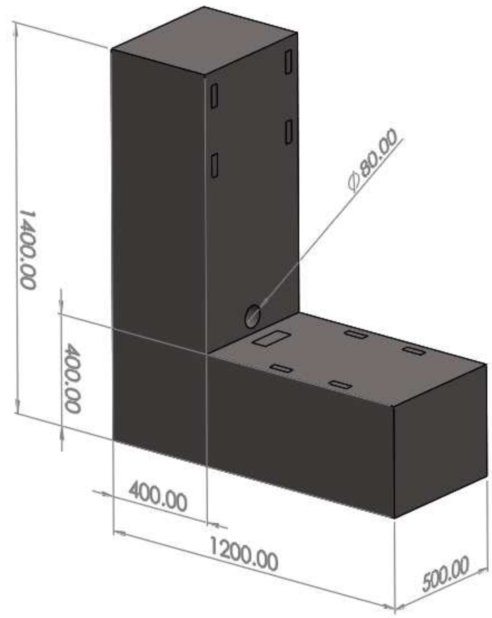

Fig. 1. Bed dimensions

There is a total of 4 versions of this model:

- the first is completely full;
- the second is a 40mm shell with no bottom so as to facilitate casting;
- the third features a triangular pattern of ribs such as the ones seen on certain cast iron parts;
- the fourth has an X pattern of ribs, similar to the triangular ribbing, but much stiffer.

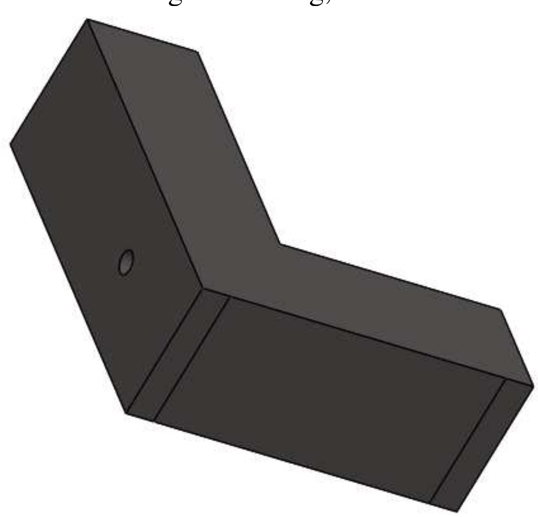

Fig. 2. Version 1 - full body

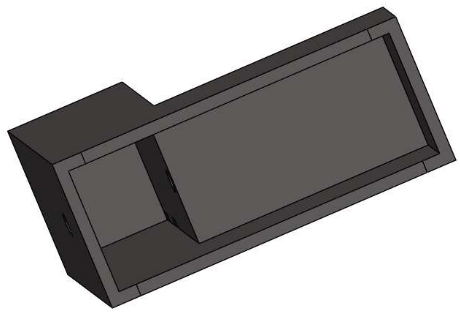

Fig. 3. Version 2 - 40 mm shell

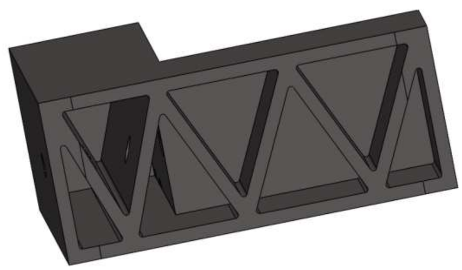

Fig. 4. Version 3 - triangular ribbing

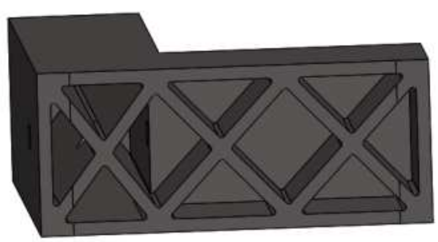

Fig. 5. Version 4 - “X” ribbing

3. NUMERICAL SIMULATIONS

Since machine-tools can usually withstand many times the forces generated during machining, the studies focus on how they respond to vibrations. Milling generates harmonic forces that when superimposed on the bed’s natural modes lead to resonance.

Resonance is in the case of machine-tools a destructive phenomenon where even a small force can cause displacements to grow to abnormal levels [1, 2]. Its effects range from the mild such as bad surface finish, low dimensional precision, tool wear and tool failure to the severe such as high wear of the machine-tool and possibly even failure in the form of machine cracks.

The machine operator can usually avoid resonance by overriding the speed and feed of the operation and in extreme cases by stopping and changing the axial or radial depth of cut, changing the toolholder or the tool. However, today’s financial challenges drive manufacturers to automate the industrial processes as much as possible and this in turn means streamlining machining so as to reduce operator intervention. So minimizing the chance of resonance and mitigating its effects becomes an important target for machine-tool builders.

The paper presents and discusses the results of the following types of analysis conducted for each of the four bed versions:

- a frequency analysis that calculates the natural frequencies and their corresponding modes of vibration of the bed in the 0 to 800Hz interval;
- a linear harmonic analysis that calculates the displacements of the bed subjected to milling using only the Y axis (the machining force acts perpendicularly on the column and an opposing reaction force on ball screw support);
- a linear harmonic analysis that calculates the displacements of the bed subjected to milling using only the X axis (the machining force acts tangentially on the column and a distributed reaction force on the space underneath the four carriages).

Figures 6, 7 and 8 show the fixtures and loads of each of the three analysis types.

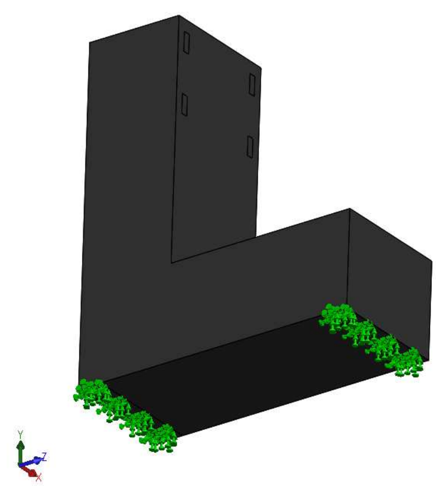

Fig. 6. Fixed geometry in green on the bed bottom

3.1. Frequency Analysis

Frequency analyses are performed in order to get a basic understanding of the frequencies at which a load acting on the bed might cause resonance. Still, a load acting at or near the natural frequencies may still not cause resonance: this is why it is important to see if their is any correspondence between the load's direction and the component's mass participation [1]. The X, Y and Z directions can be seen in the bottom left corner of figures 6, 7 and 8. It is important to notice that in Solidworks the Z direction is oriented from back to front and not bottom to top, as is the case usually.

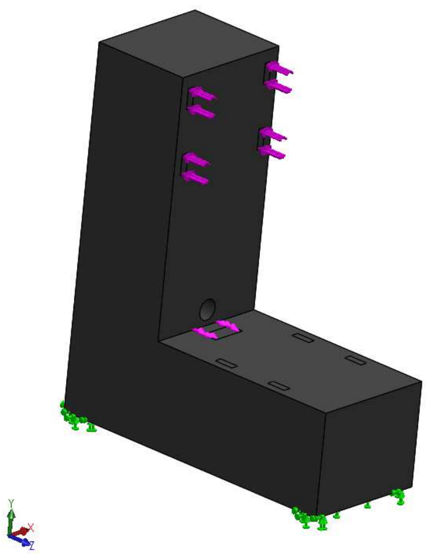

Fig. 7. Fixed geometry in green and normal force and reaction in purple

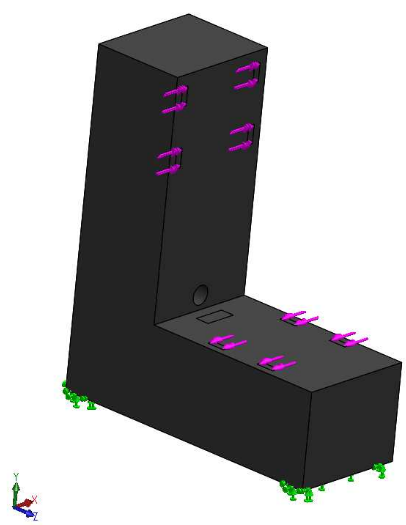

Fig. 8. Fixed geometry in green and tangent force and reaction in purple

The natural frequencies are impacted by two factors: mass and stiffness [1]. A greater mass leads to lower values and a lower mass to higher ones. It is also important how this mass is distributed: mass that is farther from the fixtures lowers the natural frequencies [2].

The component's stiffness is given by the material's stiffness and the topology of the component. This means that a stiffer material, in this case a stiffer mineral casting formulation and a bed that is fuller or has better ribbing would increase the values of the natural frequencies and space them farther apart [2].

3.1. Harmonic Analysis

Harmonic analyses are used to understand if one or more loads could create resonance. The loads used for the milling machine bed have been chosen to act either normal or tangent on the column. This simulates milling in the Y, respectively in the X direction. The forces are approximated as sinusoidal because they originate from the end-mill's rotary cutting motion.

The results of this type of analysis show the mode shapes and also the maximum amplitude of oscillation of each point on the bed's mesh. Resonance by itself isn't very damaging, unless it also reaches high amplitudes. This is when high wear and poor machining may appear and, in extreme cases, it can lead to machine-tool failure.

Displacements can be reduced by increasing the mass at the cost of lowering resonance frequencies and by using a material with better damping. Mineral casting has excellent vibration damping, far superior to gray cast iron, due to the crosslinking of the epoxy polymer which easily converts movement to heat.

4. RESULTS

Three analyses, a frequency analysis and two harmonic analyses, have been performed for each of the four bed designs, resulting in a total of 12 simulations. The results of each frequency analysis are presented as a table which contains the mode number, frequency and mass participation for the X, Y and Z directions.

A graph corresponding to each harmonic analysis presents the maximum amplitude (displacement) of the machine bed for the entire range of frequencies from 0 to 800 Hz.

4.1. Bed Version 1 (Full)

Table 3

Frequency analysis

Mode No.	Freq (Hz)	X direction	Y direction	Z direction
1	139.15	0.459	0.000	0.000
2	163.76	0.000	0.005	0.374
3	479.52	0.025	0.000	0.000
4	588.78	0.003	0.743	0.022
5	590.05	0.393	0.006	0.000
6	705.65	0.000	0.090	0.397

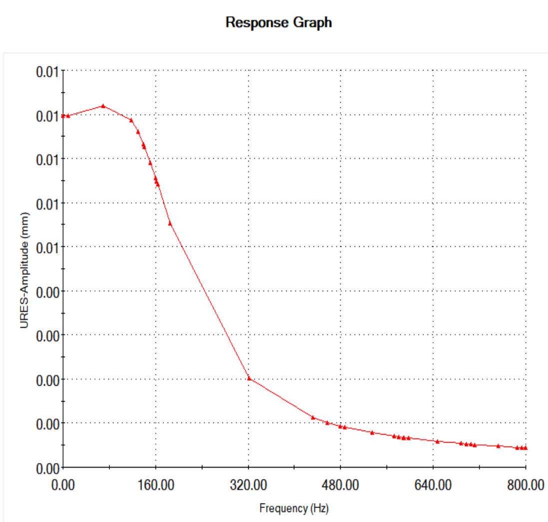

Fig. 9. Bed version 1 - harmonic analysis, normal force

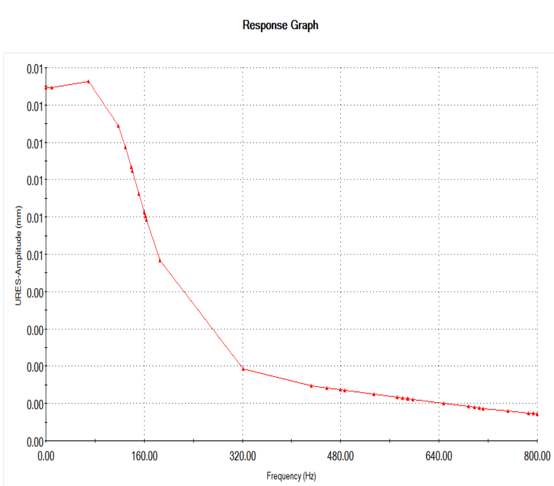

Fig. 10. Bed version 1 - harmonic analysis, tangent force

4.2. Bed Version 2 (Empty)

Bed version 2 has the same exterior shape as version 1, except that it is empty and designed as a 40 mm shell.

Table 4

Frequency analysis

Mode No.	Freq (Hz)	X direction	Y direction	Z direction
1	107.77	0.000	0.016	0.436
2	113.00	0.627	0.000	0.000
3	179.96	0.129	0.000	0.000
4	216.94	0.000	0.003	0.002
5	271.45	0.000	0.000	0.000
6	404.83	0.028	0.000	0.000
7	418.48	0.000	0.083	0.232
8	429.61	0.000	0.129	0.025
9	432.05	0.000	0.517	0.022
10	441.73	0.008	0.000	0.000
11	450.80	0.000	0.039	0.082
12	472.92	0.066	0.000	0.000
13	562.24	0.000	0.011	0.015
14	574.93	0.000	0.003	0.003
15	629.70	0.023	0.000	0.000
16	635.35	0.000	0.003	0.113
17	695.78	0.022	0.000	0.000
18	707.54	0.000	0.000	0.002
19	728.92	0.005	0.000	0.000
20	737.02	0.000	0.000	0.007
21	798.39	0.000	0.001	0.002

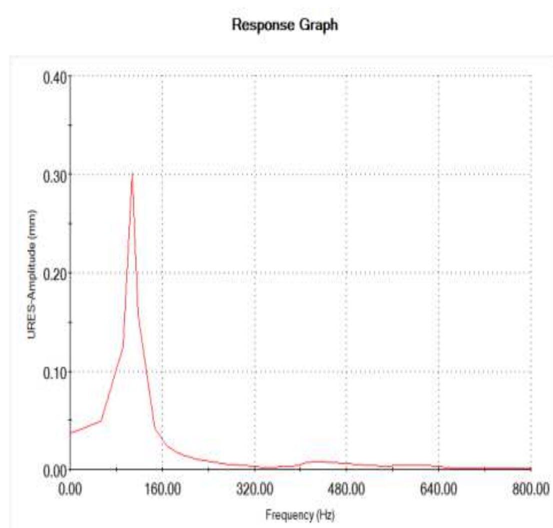

Fig. 11. Bed version 2 - harmonic analysis, normal force

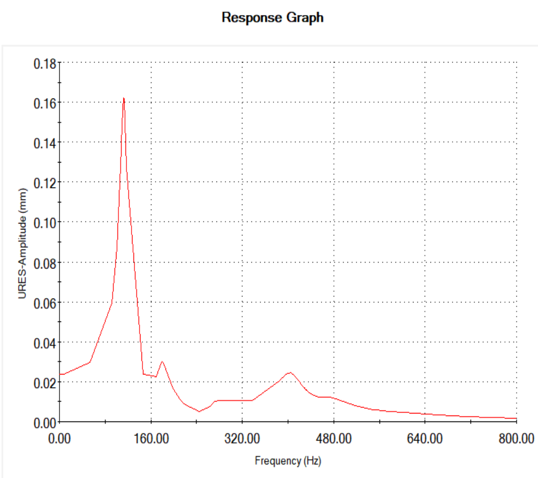

Fig. 12. Bed version 2 - harmonic analysis, tangent force

4.3. Bed Version 3 (Triangular Ribbing)

Bed version 3 adds some ribbing oriented from top to bottom to the empty shell of version 2, making it stiffer, but also heavier. This type of ribbing is typical of older cast iron machine-tools. It is relatively easy to build, but still needs a more complex mold than both the full and empty bed versions. Also care needs to be taken to give the surfaces some draft in order to be able to extract the part from the mold without destroying it. The CAD model's walls are straight and do not feature this draft since it wouldn't impact the results significantly.

Table 5

Frequency analysis

Mode No.	Freq (Hz)	X direction	Y direction	Z direction
1	103.04	0.000	0.017	0.439
2	110.66	0.497	0.000	0.000
3	323.63	0.161	0.001	0.001
4	385.89	0.006	0.044	0.423
5	411.00	0.064	0.496	0.007
6	430.18	0.174	0.260	0.011
7	533.57	0.001	0.016	0.014
8	580.01	0.004	0.000	0.000
9	624.39	0.001	0.001	0.000
10	631.34	0.002	0.000	0.000
11	657.15	0.002	0.001	0.001
12	684.91	0.000	0.000	0.027
13	704.59	0.001	0.001	0.000
14	733.31	0.000	0.006	0.009
15	776.08	0.000	0.003	0.009

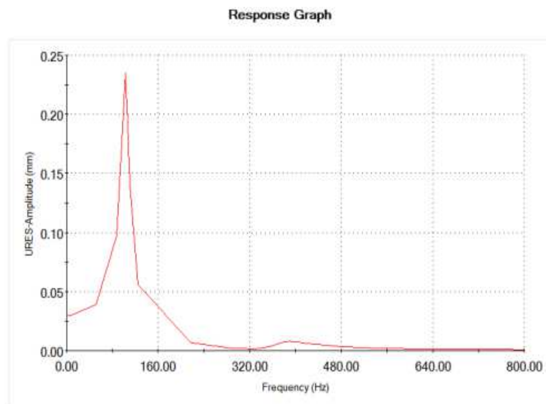

Fig. 13. Bed version 3 - harmonic analysis, normal force

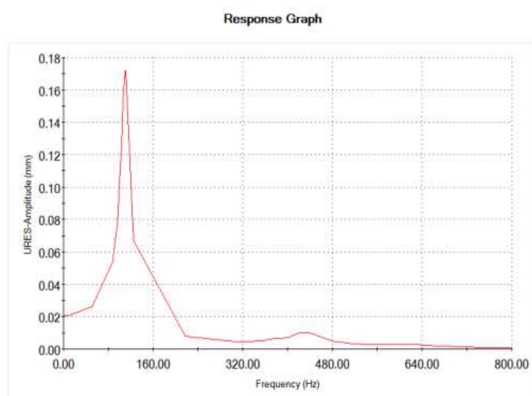

Fig. 14. Bed version 3 - harmonic analysis, tangent force

4.4. Bed Version 4 ("X" Ribbing)

Bed version 4 has an extra stiff ribbing pattern. The "X" ribbing is used in many car and plane parts, but also in civil engineering because of its benefits and simplicity. It prevents the part's diagonals from extending or shortening and can be fabricated the same way as the triangular ribbing.

Table 6

Frequency analysis

Mode No.	Freq (Hz)	X direction	Y direction	Z direction
1	109.47	0.000	0.014	0.430
2	115.10	0.484	0.000	0.000
3	341.77	0.074	0.000	0.000
4	431.43	0.000	0.269	0.211
5	435.41	0.000	0.536	0.244
6	436.08	0.343	0.001	0.000
7	608.09	0.000	0.009	0.014
8	628.29	0.020	0.000	0.000
9	684.97	0.000	0.001	0.000
10	706.63	0.000	0.000	0.000

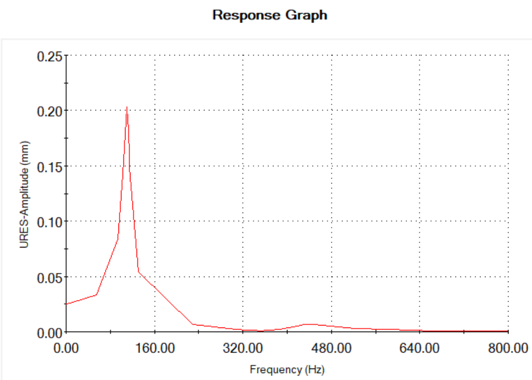

Fig. 15. Bed version 4 - harmonic analysis, normal force

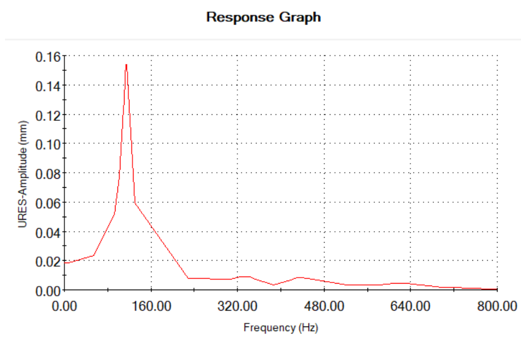

Fig. 16. Bed version 4 - harmonic analysis, tangent force

5. COMPARING THE RESULTS FOR THE FOUR BED DESIGNS

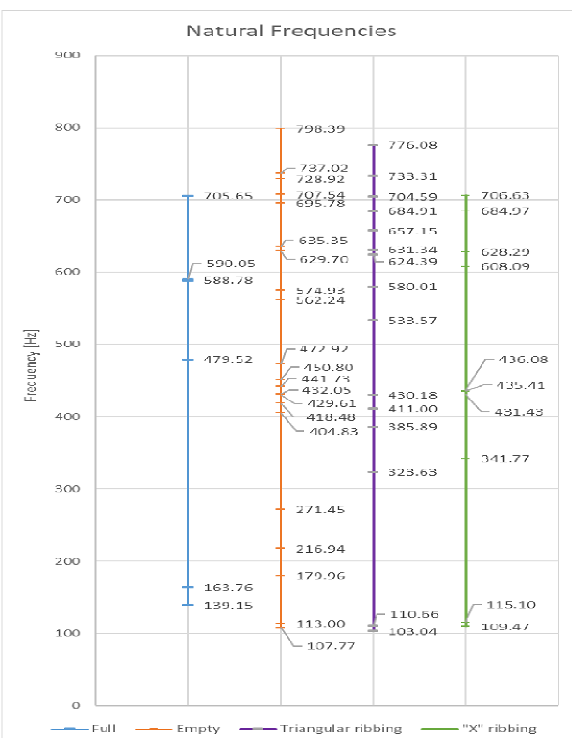

Fig. 17. Comparison between the natural frequencies of the four bed designs

Figure 17 shows that the full bed has the fewest natural frequencies, 6, in the range of 0 to 800 Hz. As material is removed from it, the number of frequencies increases. Thus the “X” ribbed bed has 10 natural frequencies, followed by the triangular ribbed one with 15 and the shell with 21.

The same order is followed in terms of maximum displacement of the beds. The full design has the smallest amplitude, the “X” ribbed one follows, then the triangular ribbed one and finally, with the largest displacement is the shell design.

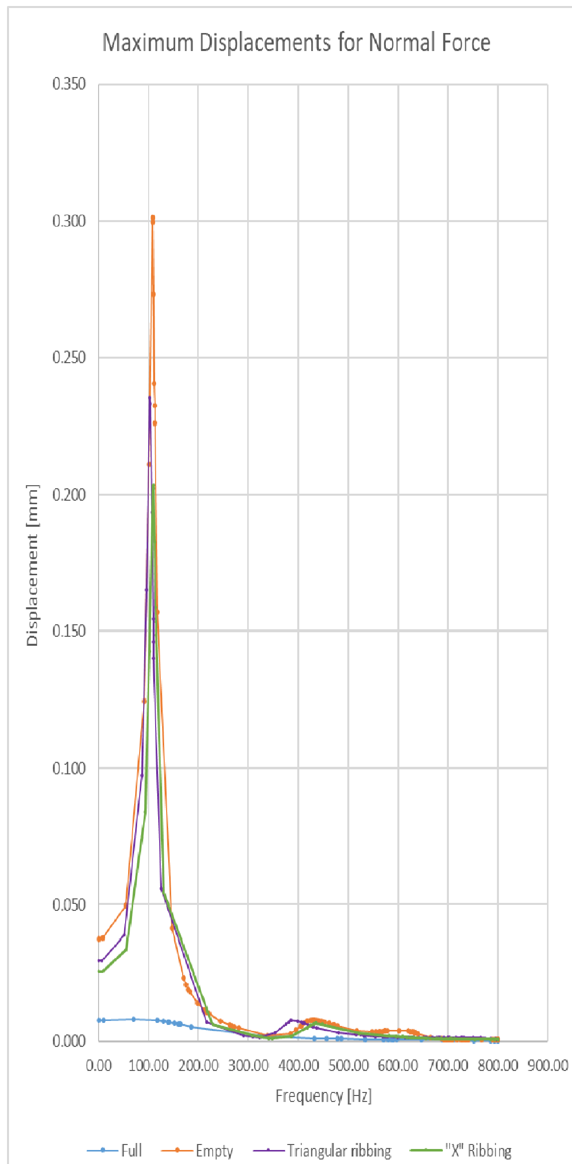

Fig. 18. Comparison between the maximum displacements of the four bed designs when subjected to normal loading

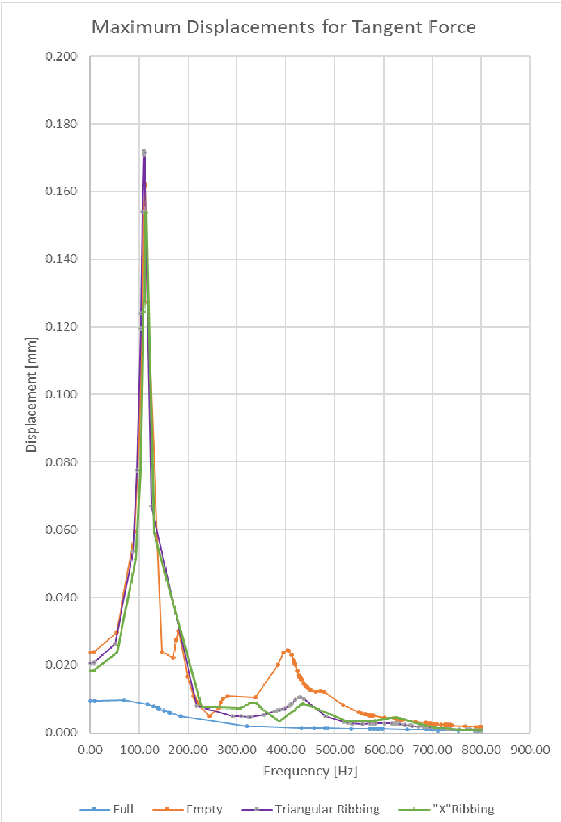

Fig. 19. Comparison between the maximum displacements of the four bed designs when subjected to tangent loading

CONCLUSIONS

The different analyses carried out for the four bed designs show that the stiffest bed, the full one, has the least number of natural frequencies in the 0 to 800Hz interval. It has only 6 compared to the 21 of the shell bed. This is a 71.4% decrease in the risk of hitting resonance if the full bed design would be chosen compared to the empty one. However this problem is improved by using triangular ribbing and even further by “X” ribbing.

Bed version 1 also excels in how it handles resonance situations: it has small displacements for both the normal and the tangent forces. This is not a coincidence since a higher mass lowers the resonance amplitude.

So the question that arises is why not simply use a full cast bed? It performs very well and has the simplest mold of all the four designs, so this should be the best choice. However, a full bed costs significantly more because of the extra material required to make it and is much heavier making transport and handling more difficult and expensive. Another disadvantage is the fact that epoxy resin undergoes an exothermic reaction when hardening and this process could result in stresses and deformations or even cracks in the absence of controlled thermal management of the process.

The results show that an “X” ribbing pattern offers very good performance in terms of vibration damping and it does it for a much smaller cost than the full bed.

8. REFERENCES

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ANALIZA DINAMICĂ ȘI COMPARAȚIE INTRE DIFERITE MODELE DE BATIURI DE MAȘINI DE FREZAT REALIZATE DIN COMPOZIT MINERAL

Rezumat : Mașinile-unelte reprezintă un domeniu fundamental în inginerie. Tot mai mulți constructori de mașini-unelte au început să folosească materiale compozite, în special o clasă de betoane polimerice denumite compozit mineral, care sunt folosite pentru realizarea de componente structurale precum batiuri, coloane, mese, portale etc. Lucrarea prezintă un batiu simplificat de mașină de frezat în 3 axe, proiectat de autor, și o serie de analize numerice care simulează comportamentul piesei atunci când e supusă vibrațiilor rezultate din așchiere. Patru modele diferite de batiuri sunt studiate pentru a evalua câteva forme uzuale. În urma studiilor, nervurarea se dovedește a fi un compromis bun între cost și performanță, ambele fiind criterii importante.

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