

Original Article

Performance Analysis and Design Optimization of Single-Column Key Components Composite Machining Centers

Yuchun Miao¹, Jamaluddin Abdullah²

^{1,2}Mechanical Engineering, Universiti Sains Malaysia-Engineering Campus, 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia.

²Corresponding Author : miaoyuchun@163.com

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Abstract - Using the LH-450S prototype, this research is focused on investigating the dynamic and static properties of key structures of the V/H machining systems of a singular column. ANSYS-based Finite Element Analysis (FEA) proposed the analysis of vibrational and vibrational response under the load situation. The preliminary static analyses showed that the stiffness of the Z-axis was 3630 N per mm at static conditions, indicating a need for reinforcement of the structure. At 42.8 Hz, the primary natural frequency presented some risk of resonance from the fact that it coincided with typical spine speeds. In addition, thermal modelling showed that there is a deviation of 0.08 mm at the tooltip under a gradient of 40°C. Through some geometric and material changes, the Z-axis rigidity increased, and the modal frequency of the first mode increased to 48.6 Hertz. The optimisation strategies were also tested based on structural performance, but on manufacturability and industrial feasibility, so that the potential modifications can be produced in reality in the existing machining centre production systems.

Keywords - FEM, Structural mechanics modelling and design, Design against vibration, Mechanics of materials, Design and manufacturing.

1. Introduction

The trend towards Industry 4.0, the development of smart manufacturing, has resulted in an urgent requirement for machine tools with multi-functionality, high speed, and extreme precision. Current industrial domains, such as moulding and manufacturing, need machining centres for better stability. These systems give the needed freedom in manufacturing [1]. Within this landscape, the single-column horizontal and vertical composite machining centres have become essential machines since they allow for various processes, such as tapping, boring, milling, and drilling (which are performed one after the other, or singularly). These machines combine the horizontal and vertical axes in many cases, sometimes through advanced CNC multiple-axis control, to boost the efficiency of machining as well as reduce the preparation time.

However, with ever more complex manufacturing tasks and ever tighter tolerance standards, the structural strength of these types of machinery is frequently a limiting factor in achieving a consistency of product standard. Common problems include the erosion of the tool prematurely and inaccuracy in the dimensions. As highlighted by the results

of [2], such factors are directly related to the overall performance of the machine. These problems occur due to static load on the structure. The precision and durability of systems, such as those used for electrochemical machining, are very limited by the construction of major elements such as the interface of the tool, the crossbeam, the machine bed, and the spindle column. For this reason, comprehensive knowledge of the dynamic and static behaviour of these parts is the key to optimizing the performance of these machines.

To meet these needs, engineers have simulation software like Finite Element Analysis (FEA) and FIHL to predict the structural behaviour. It finds the problem in the structure due to dynamic and thermal loadings. By using advanced software like ANSYS, researchers can create complex 3D models with real-life boundary parameters to test the frequency, displacement, and stress [3]. Furthermore, the use of FEA speeds up the machine tool development process by reducing the use of physical prototypes.

The only significant gap identified in the literature is the absence of a multi-physics analysis, with consideration of both the dynamic behaviour and the static stiffness, as well



as thermal aspects of single-column composite machining centres. Also, available optimisation strategies tend to focus on single-objective optimizations (stiffness optimisation, or weight optimisation) and do not consider the trade-offs between rigidity, vibration stability, and thermal deformation adequately. Further, research on industrial-scale machines, including the LH-450S, with validated simulation models together with literature benchmarking is very scarcely done.

This fact results in a lack of precision in the machining itself, higher operational risks (resonance), and a longer-term structural degradation because it is not possible to predict and optimize the coupled static, dynamic, and thermal performance of the single-column machining centres. It is not easy to determine the key weak areas due to the lack of an integrated approach of design and analysis, especially on the Z-axis and spindle-column interface, when deficient in applying effective design changes.

This type of research is centred on the LH-450S horizontal/vertical composite machining centre, which is considered an industrial standard for these applications. The research takes advantage of FEA tools to study the modal and static properties of LH-450S in order to identify any important structural flaws. These effects of the simulation are checked from two previous academic works by [4], who studied horizontal machining centres, and [5], who analysed the behaviour of the composite columns with different loads. There is no integrated multi-physics study that carefully takes into account both the static stiffness, dynamic vibration, and the thermal deformation in a single regard. The main purpose of this research is to suggest design changes that increase rigidity, reduce vibration, and reduce thermal deformation of the essential parts.

Further, existing studies have been predominantly single-objective based, such as maximising rigidity or minimising weight, and do not take into consideration the underlying trade-offs between rigidity, vibration control, and thermal accuracy. Moreover, no literature exists that is devoted to industrial-level composite machining centres, such as the LH-450S, and the validation of the simulation findings is little developed with references to the multiple literature sources.

2. Literature Review

The proposed research is an original consolidated method of studying and optimizing the single-column composite machining centres. The current work integrates all three aspects of the existing research. The work considers the three features in one multi-physics, FEA model as opposed to the current research methodology, which observes these factors independently. It also presents a combination of stiffness, vibration stability, and thermal deformation multi-objective optimisation strategy. The study also presents a

practical validation focusing on the use of the case of industrial LH-450S in comparison with previous studies, including [4, 5]. It further suggests an integrated material-geometry optimisation, which improves the structural performance and machining accuracy.

2.1. Composite Machining Centres

The high rate of manufacturing of precision engineering resulted in the usage of single-column horizontal and vertical composite machining centres as key equipment required to undertake the tapping, drilling, and milling processes in one setup. This improved productivity leads to the reduction in repositioning of parts and the reduction of alignment errors, and the multi-functional centres of machining help in this. The device structure, the accuracy of the control, vibrational, and thermal performance determine the machining quality.

According to the recent research [6], the industry 4.0 demands have resulted in the further design of modern machining centres being multi-axis, flexible, and high-speed, precise. These systems have been combined with smart control systems and real-time monitoring, making it even more efficient and adaptable in the way it operates.

Nevertheless, single-column systems have challenges associated with asymmetry of loads, amplification of vibration, and distortion of heat, which are posed by the structural configuration, and they have a significant impact on machining accuracy.

Split by design, the machine breaks into two key parts, the seating section and the cutting part (see Figures 1 and 2). The part of the seat consists mainly of the rotary table, saddle, and base, and the machining is hanging from the vertical column (Figures 3 to 8). This consists of the column, the vertical machining head, the vertical tool changer, the horizontal machining head, and the horizontal tool changer.

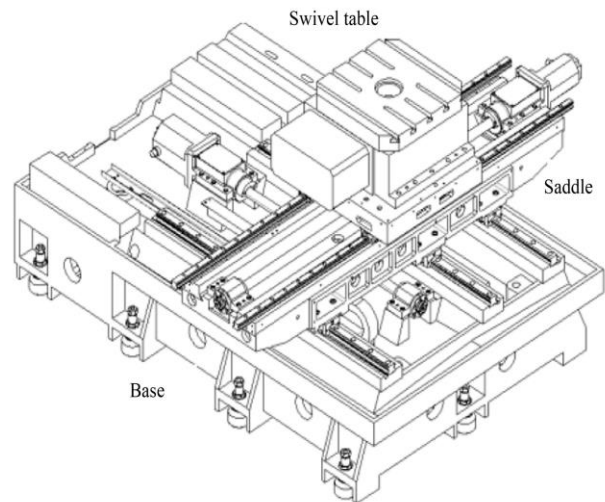


Fig. 1 Structure of seat

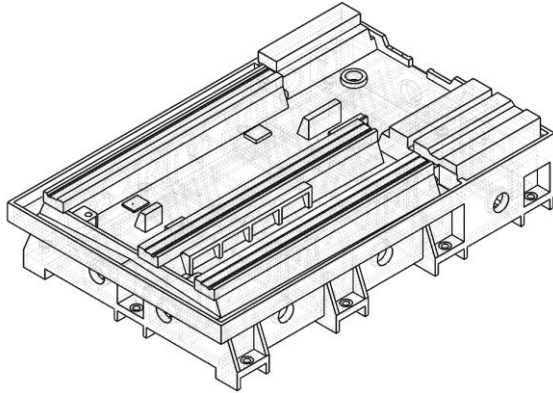


Fig. 2 Structure of base

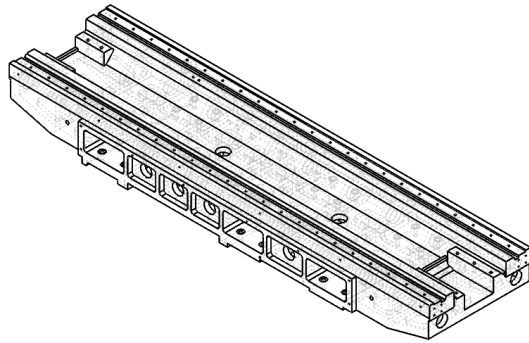


Fig. 3 Constriction of saddle

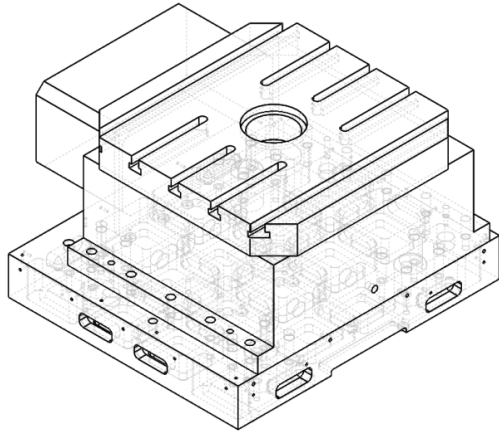


Fig. 4 Structure of turntable

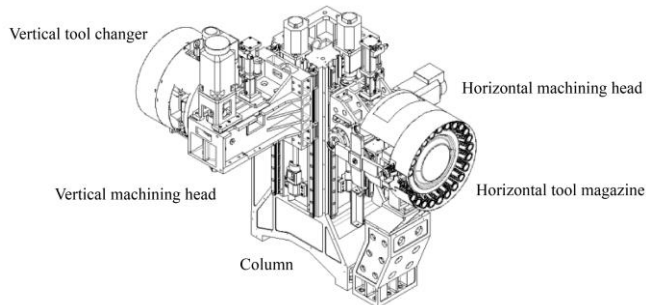


Fig. 5 Processing department structure

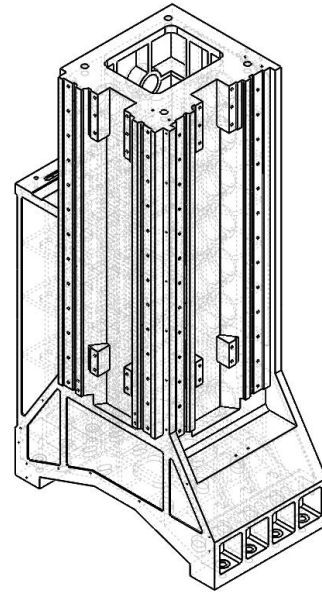
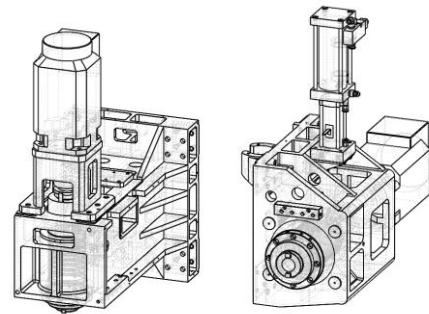
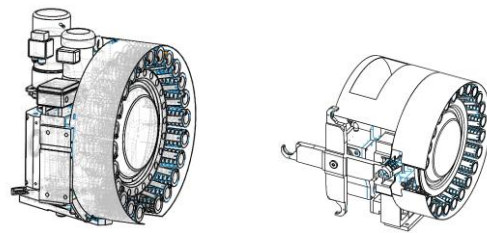


Fig. 6 Structure of column



(a) Spindle boxes (Vertical) (b) Spindle boxes (Horizontal)

Fig. 7 Structure of spindle box.



(a) Vertical tool changer (b) Horizontal tool changer

Fig. 8 Tool magazine structure.

Composite centres function by mixing the horizontal and vertical setups, so the requirement for space is less. Because of [7], it is known that this mix offers an affordable way to stay flexible when making moderate to large batches of custom components. The use of the double-axis tool causes a lot of problems. The behaviour of the frame and its stiffness are issues in this case, which can impact the quality. Despite the benefit that this configuration provides, the usage of a dual-axis tool creates serious challenges concerning modal

stability, structural stiffness, and thermal regulation. These factors can seriously affect the integrity of the surface and also increase the wear of the tool. To combat such problems, research commonly relies on FEA as the main framework to simulate and adjust the design [6]. Consequently, this work firstly takes into consideration the recent developments on structural optimisation and vibration, and thermal management of composite machining centres using FEA-driven optimisation.

2.2. Composite Machining Centres

Machining precision is especially based on structural rigidity. Stiffness in the system causes the tool to deflect, and there is deviation every time the machine is run. The singular column architecture centres of composite machining are highly prone to torsional and bending fatigue subjected to dynamic or asymmetric loading. Research conducted by [8] shows that there is a simultaneous deformation in radial and vertical values in the columns. However, structural rigidity can be increased significantly with the foundation thickness using ribs with reinforcement.

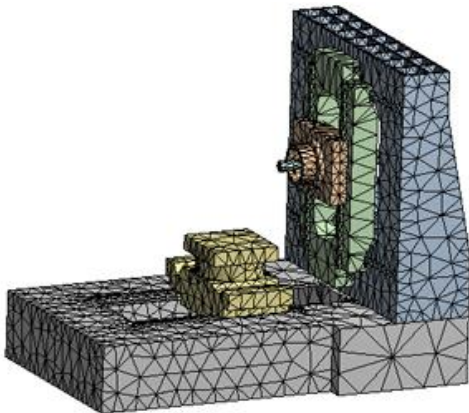


Fig. 9 FE Model of a machining centre (Source: Liang et al., 2013 [5])

Finite Element Analysis (FEA) is a key tool that can be used to simulate and improve this rigidity (Figure 9). As an example, structural analysis, which is static in nature, by [9] showed that cast iron could be replaced with an alloy that is hybrid in an aluminium structure. In combination with optimized cross-sectional geometry, to be 18% lighter while having a 14% increase in stiffness. These authors stress the importance of material choice and geometric stiffening in achieving a balance between inertial loads and want to prevent excessive inertial loads. The majority of the research, however, deals with isolated stiffness improvement, but their combination with dynamic and thermal behaviours is neglected. This weakens the application of the research to actual machining industries. Furthermore, localised deformations occur frequently at the tool interface as a result of stress concentration (near bolt-holes, mounting faces, etc.). To overcome this issue, [11] suggests FEA iterations to improve fillet radii and the load-spread flanges at key points.

2.3. Vibration Characteristics and Modal Analysis

Vibrational stability is the key to machining at high speeds since, in practice, the complex structure of composite centres typically results in natural frequency coincidences to operational speeds, as this results in resonance and poor surface quality. Modal analysis is applied to find these frequencies and forms. For example, [6] showed that the initial 3 modes of vibration in a seven-axis V/H machining centre were caused by the slender tool column and crossbeam serving as amplifiers for the vibration.

When MI increases, the natural frequency also increases by 21%. It improves the cutting stability of the machine. In addition to this, infusions of polymer composites into basic structures provide better damping characteristics. In works by [11], it was shown that the beds of composite-polymer, which are hybrid in nature, offered a lower maximum stress of vibration by 37% compared to conventional cast iron alternatives.

[6] have determined that slender columns and crossbeams were vibration amplifiers, whereas [11] demonstrated that polymer composite beds are much more effective in terms of damping performance. With these developments, current research mainly examines vibration, excluding structural stiffness and thermal attributes, which restricts its ability to predict the actual machining circumstances.

2.4. Thermal Effects and Compensation

Precision in machining is adversely impacted by thermal differences. Thermal effect in tool holders, beds, and spindles causes positional inaccuracy, which is especially prominent in centres of composite machining because of prolonged use and non-symmetry of loads. According to [12], temperature gradients along the spindle shaft cause micrometric displacements of the tip to cumulate and weaken machining tolerances. Thermal FEA is used to locate important hot spots in the area of spindle bearings and motor mounts.

Building on these simulations, which used the coupling of thermal-structural nature in the ANSYS Workbench, [13] used the Workbench to engineer routing channels of coolants within the spindle housing. This design intervention helped reduce the maximum thermal change by 32% and ensured a more uniform distribution of temperature along the axis of a tool.

Despite the merits of passive thermal management through ventilation and low-expansion materials, such as ceramics, these types of management are often inadequate. Trends of the present day are changing and moving toward active compensation, making use of machine learning and sensor integration that compensate thermal deviations dynamically. Crucially, these intelligent systems need to be shown using FEA-generated data in order to effectively predict and counter the effects of heat through the structure.

[12] have mentioned that temperature variations in spindle networks drive variations at the micrometre length scale, whereas [13] indicated that application of coolant channel optimisation can decrease thermal deformation by as much as 32%. The recent studies emphasize the importance of thermal compensation systems that rely on machine learning, which are also demonstrated to use sensor data to modify machining parameters in real-time. These systems, however, demand a precise simulation model to be trained and verified.

2.5. Optimisation of Key Component Using Finite Element Analysis

Besides the area of structural frames themselves, however, optimizing certain machine elements such as cross sliders, tool magazines, or spindles is crucial to performance. High-precision Finite Element Analysis (FEA) is a very important pre-validation tool that can give feedback for design iterations before actual physical prototypes are constructed. For example, [14] used topology optimisation to redesign the mount, which successfully reduced the mass by 23% without affecting the required stiffness levels and with improved stress distribution under operational loads.

FEA also plays an important role in predicting fatigue life. [15] used ANSYS fatigue modules to find out the effect of cyclic loading in spindle bearings. Also, finding its effect on straight guideways in horizontal centres. Their computation results were in good agreement with experimental results for the endurance, proving that digital modelling is a reliable way to speculate long-term wear. In addition, component-level analysis has been done for the dynamics of tool change. Modelling of impact forces in carousels showed that predicting and placement of liners with shock absorbing material between the mountings has the potential to reduce maximum stresses by an amount of 29%. This holistic method of simulation is important to making sure that individual parts add to the overall reliability and efficiency of the machining system.

[14] used topology optimisation to control the mass of components at the expense of the stiffness, and [15] employed fatigue analysis to determine structural behaviour in the long term. However, the majority of optimisation strategies are singly-objective and are based on stiffness or weight minimisation and do not address multi-objective trade-offs between stiffness, vibration, and thermal deformation.

2.6. Advanced Materials in Optimisation of Structure

Such as hybrid alloys, concrete polymers, and carbon fibre composites are preferred over traditional cast iron, however, because of lower cost and simplified casting processes. Specifically, polymer concrete-based materials have been demonstrated to be able to enhance vibration absorption by a factor of 1.8 without reducing heat

conductivity [16]. Researchers use FEA to simulate load-carrying paths to compare the simulated damping behaviour and experimental results.

According to [16], polymer concrete can be used to achieve a significant increase in vibration damping and simultaneously reasonable thermal characteristics. Nevertheless, it has difficulties in providing the interfaces of materials and bonding behaviour that are simplified in FEA simulations, lowering the precision.

2.7. Sensor Integration and Smart Control

The use of live control and sensor integration has become an essential aspect of modern manufacturing in the area of turning centres. These systems require simulated models and prescribed response strategies to be successfully trained. Discussed digital twin issues using live sensor data to refresh virtual FEA models to monitor behavioural prediction. An example where this would actually have a practical application is with spindle temperature sensors providing information to thermal FEA models to predict and compensate for tool displacement. Furthermore, the possible new AI, called optimizing assisted AI, is gaining momentum. [17] showed that combining an FEA simulation dataset using neural networks is feasible to predict the optimal working conditions for specific tool types and geometries.

Digital twin frameworks and an update of FEA models by real-time sensor data were demonstrated, whereas predicting optimal machining conditions on the basis of AI-assisted optimisation was demonstrated by [17]. In spite of all that, the involvement of FEA models and real-time control systems has not yet become integrated, which is the gap between simulation and practice.

2.8. Future Trends and Research Gaps

Despite a substantial amount of literature on the structural and thermal vibrational optimisation of machining centres, there are still some critical research voids. Currently, FEA applications are mostly offline, limiting their usefulness in the real-time adjustments of operations. A major gap lies between these high-fidelity simulations and the digital twin services needed to enable live decision-making and predictive maintenance. Furthermore, today's optimisation strategies often target single objectives, e.g., weight reduction or stiffness, instead of covering the complex trade-offs between optimal structural stiffness, vibration, and thermal stability, damping, or material costs in a multi-objective hybrid approach.

While high-end materials, like composites of carbon fibre and polymer concrete, are being used more, the modelling of interface bonding and boundary condition behaviours between bulk composites and materials is not well managed in typical FEA environments. Further, systems to compensate for undeformations of the spindle in real-time,

especially in the direction of degradation of the toolpath by fingertip deformation and differences from the raw toolpath, are, on the whole, in their infancy. Future research efforts will be expected to shift toward AI-based predictive models, feedback loops based on FEA in real-time, and integration of entire systems that are cyber-physical into full cyber-physical machining environments to produce truly autonomous machining environments accordingly.

2.9. Literature Review Conclusion

The current literature does confirm the fact that FEA is an indispensable tool for the simulation, design, and refinement of composite centres. Research proves that FEA is effective for improving the rigidity of structures against vibrations, thermal expansion, and the optimisation of critical components. Furthermore, the combination of digital twins and smart sensors provides fresh possibilities to help coordinate the data with real-time machine results.

Despite these advancements, the ever-increasing complexity of the present systems requires ever-adaptable, interdisciplinary, and integrated approaches. This topic helps connect the ANSYS model with practical examples. Testing is the proper way of developing such a tool rather than depending completely on theory. When an idea goes through the experimental phases, only then does it become of such a level that it can be implemented.

The given research attempts to fill such gaps by introducing a multi-physics, multi-objective optimisation framework, which is tested with an industrial-size LH-450S machining centre, thus obtaining a more holistic and practical solution. Using these materials leads to bonding problems. It can also cause thermoelastic mismatch. Thermal-mechanical FEA analysis carried out by [18] on the joint of carbon metal showed that steep corners in the bonding areas are highly affected by stress concentration. Consequently, design improvement with interface transitions that are rounded and reinforcements that are adhesive to ensure the structural integrity has been proposed.

Nonetheless, these studies have a major limitation: none of them has integrated analysis that would address the effect of fixed, dynamic, and thermal relationships coherently through a single framework. This experiment builds on the current body of work in the literature by incorporating multi-physics FEA, multi-objective optimisation, and checking its findings against a set of previously documented literature findings. Thus, presents a more comprehensive and valuable, basically applicable design amalgamation of composite machining centres.

3. Methodology

This investigation makes utilisation of a multi-methodological approach to analyse and improve the dynamic and static characteristics of essential parts in single-

column V/H machining centres. This study is specific to the application of these methods on the LH-450S horizontal/vertical dual-purpose centre by ANSYS-based modelling and simulation. Methodological development is based on two important peer-reviewed works of [4, 5]. These sources give the foundation required for modelling stiffness of the structure, modal behaviours, static and dynamic integrated behaviour of composite structures, and machine elements.

3.1. Overview of Methodological Framework

The study design is a combination of the FEM, case studies, and literature benchmarking. The choice of FEA based on ANSYS is explained by the fact that it can solve coupled structural, modal, and thermal problems being investigated based on continuum mechanics with high accuracy. ANSYS Workbench 2023 R2 was used to run the simulations (if not stated otherwise): The Statistical Structural, Modal, Thermal, and DesignXplorer modules were used to make the experiment reproducible.

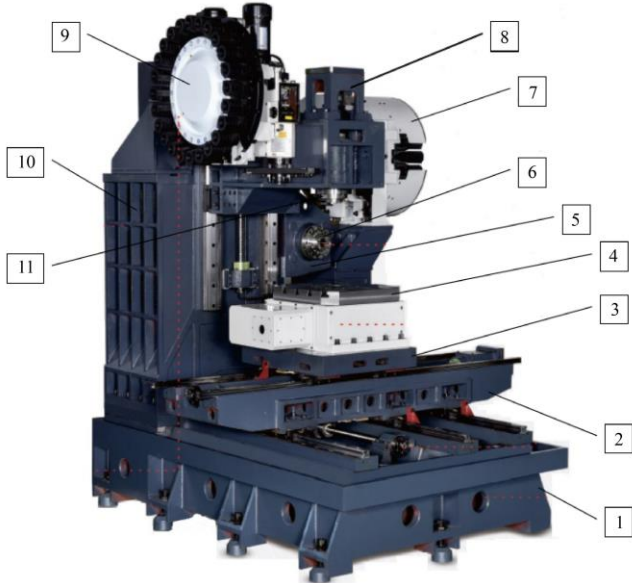
All the simulations were run under uniform conditions of solver with consistent boundary conditions, convergent criteria of 10^{-6} of residual forces, and adaptive meshing. The LH-450S machining centre is known to be a linear elastic system, assuming that small deformations are observed, material isotropic behaviour is observed, which holds well with established literature [4, 5].

Such assumptions can be computationally efficient as well as provide enough accuracy in the prediction of structural performance. Literature benchmarking will allow grounding simulation outputs on the theoretically validated experimental models.

3.2. Case Study of LH-450S

The LH-450S horizontal/vertical dual-purpose machining centre was selected because of its use of industry-standard precision with structural stability. This system has a symmetrical, thermally stable system with a high-spindle speed fitted with a bed with single-column, spindle housing, crossbeam, and a magazine for tools. As an example in Figure 9, the structural layout was replicated by using CAD and ANSYS as a benchmark for validating the modal frequencies, static stiffness, and optimization strategies under operational conditions.

The machining centre, which was chosen to be LH-450S, was industrially relevant. The dataset comprises CAD-based geometry, ANSYS-based material properties, 2000 N in three directions loading, and a thermal gradient of 40 °C. Consistency and standardisation in the case of the inputs meant that the simulations were the same, and this allowed robust testing of structural stiffness, vibration behaviour, and thermal deformation properties.



1. The Base; 2. The Saddle; 3. The Rotary table connecting base; 4. Rotary table with precision horizontal cam roller; 5. Spindle box (Horizontal); 6. Spindle (Horizontal); 7. Disc tool magazine (Horizontal); 8. Spindle box (Vertical); 9. Disc tool magazine (Vertical); 10. Column; 11. Spindle (Vertical)

Fig. 10 LH-450S machining centre

For making the FEA Model, 3D models of different parts are made in Workbench. Minor slots, withdrawal grooves, and fillets with a size of less than 30mm were eliminated for the sake of computation efficiency. It is this tetrahedral mesh that is illustrated in Figure 10 and which incorporates refinement zones in high stress areas such as the column-bed joint and the spindle base.

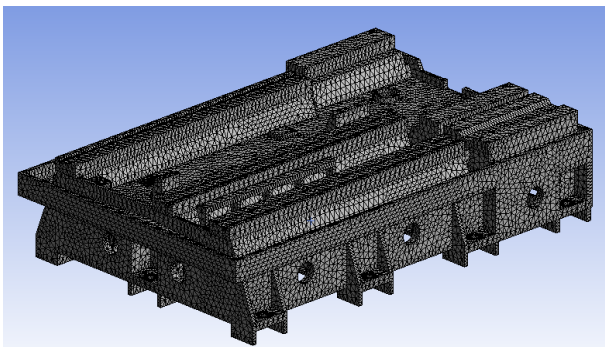


Fig. 11 Chassis components meshed

Various modelling assumptions were added to give some trade-offs between computational effectiveness and physical realism. To begin with, small geometric elements like fillets (that have a diameter less than 30 mm) were eliminated, because the impact of such geometric elements on both global stiffness and modal properties is insignificant, although they severely complicate the mesh. Second, the materials were

believed to be isotropic and homogeneous, which is in line with FEA traditional practice of machine tools structures, and which previous research studies justified. Third, fixed and what are known as frictionless conditions of contact were used to model the rigid connections and sliding interfaces, respectively, on the behaviour of real assemblies to machines.

Material properties were assigned according to structural steel and cast-iron data, and the damping coefficients in joints have been integrated based on the results of [4]. The model was based on bonded and frictionless interactions, which were used to mimic the mechanical constraints of the real world.

3.3. Static Analysis of Structure

The stiffness and deformation properties of the centre were examined by static analysis under some simulated operational loads and fixed boundary conditions. Individual forces of 2000N were applied to the worktable and spindle head in the Z, X, and Y axes to reproduce standard clamping and cutting pressures. For realism of anchoring, the machine base was completely restrained, as shown in the stress cloud in Figure 12.

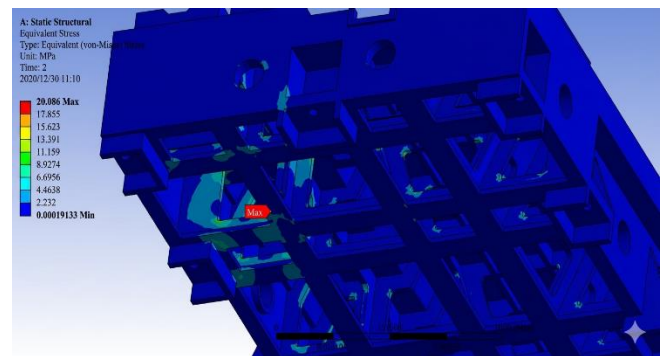
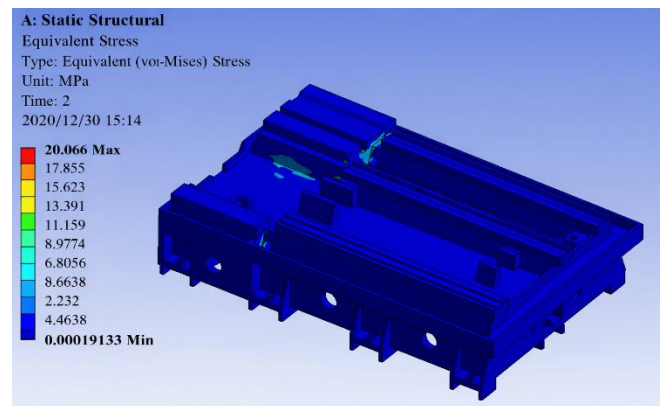


Fig. 12 Stress cloud of base assembly

Data about von Mises stress, strain, and displacement distributions have been recorded during the simulation. Rigidity for each of the axes was obtained from the stiffness formula.

$$K = \frac{F}{\delta}$$

in the ANSYS Workbench environment, where F is the applied force, and δ is the displacement (Figure 4). Following the methodology of [4], in this investigation, the Z-axis was investigated first because of its great importance in the vertical deformation. The resulting data was used to inform the proposal of structural reinforcement strategies, the aim of which is to mitigate high concentrations of stress and increase precision and integrity of machining under load.

3.4. Modal Analysis

ANSYS was applied to perform the modal analysis of the composite machining centre, which helps to find out the

dynamic properties, the mode shapes, and natural frequencies. The solver employed was block Lanczos, and regular boundary conditions as are provided in the case of the static analysis.

The data set comprises a number of frequencies (0 to 100 Hz) to represent operational resonance conditions. To replicate a fully constrained base, certain BC were applied, as well as extracting the initial 6 mode shapes, as shown in Figure 13. Following the established methodologies of [4] and [5], the analysis targeted the bed-worktable and the column-bed interfaces as sites of primordial amplification of the vibration.

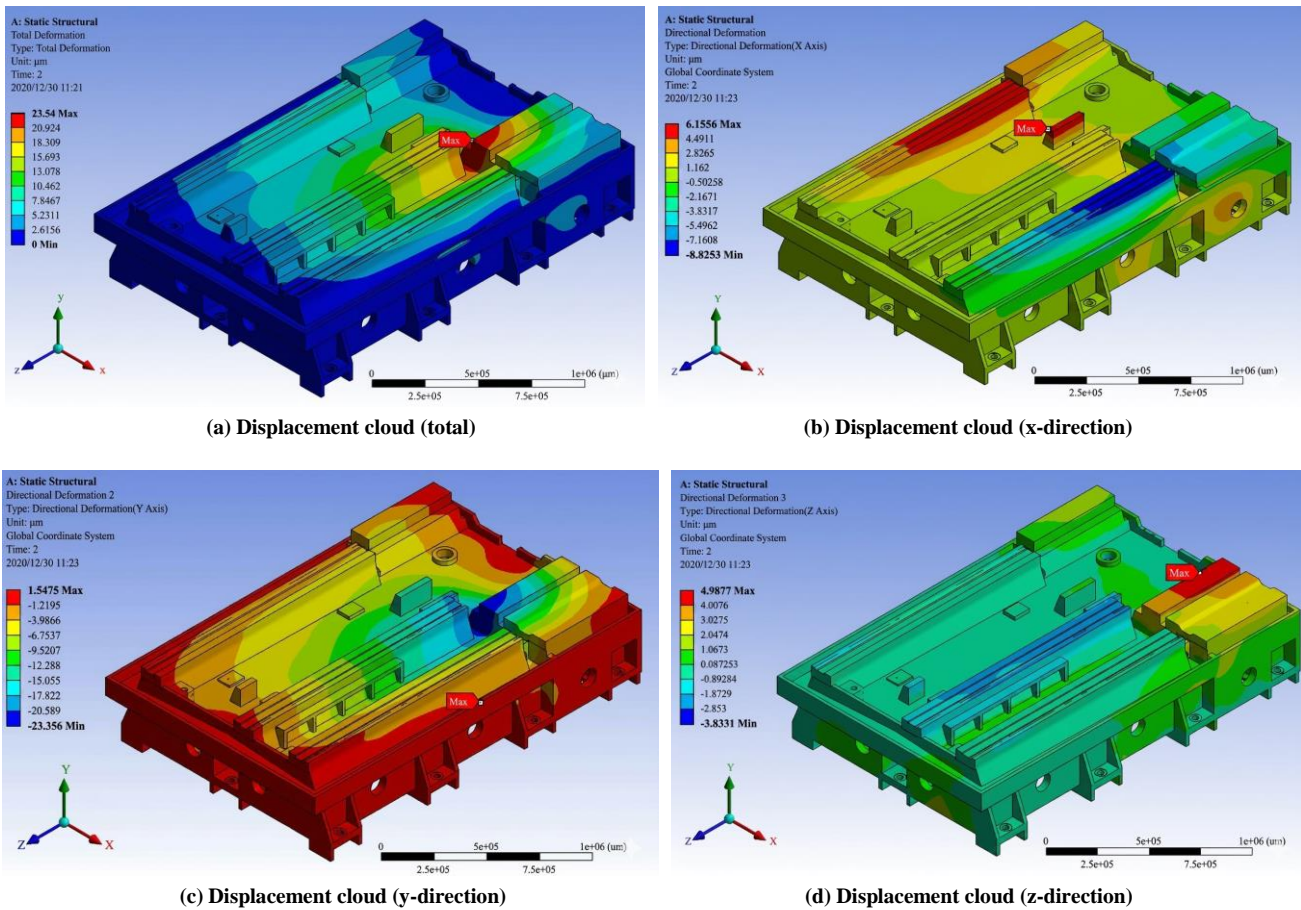


Fig. 13 Displacement cloud of base assembly.

Findings revealed that the normal machining speed of 40-50 Hertz is the primary natural frequency, which makes it susceptible to natural frequency excitation when machining tasks are performed under a standard mid-speed machining operation method. The dominant mode shapes consist of torsional and bending vibration in the crossbeam and column, giving rise to the notion that focused reinforcement in areas may be a very efficient way of curbing vibration. Ultimately,

this analysis is used as a guide for making improvements in the design that are supposed to increase the dynamic stability and to perfect the quality of the machining surface.

3.5. Literature-based Comparative Evaluation

In order to ensure the accuracy of the simulation results, they were benchmarked in comparison with the modal and static analysis of [4, 5]. Regarding static stiffness, the present

research is similar to the results obtained from Liang's study, as the Z-axis was at the most vulnerable direction with a stiffness value of 3630 N per mm. The modal frequencies obtained in this model, i.e., the first mode between 42 and 45 Hz, show a further confirmation of the frequencies reported by [4].

Furthermore, patterns of deformation and stress found at the spindle joints and columns agree with the environmental vibration in terms of modal increment zones seen in composite columns, which are steel-covered by [5]. These correlations confirm that the FEA simulation framework is a useful tool to describe the behaviour of machine tools. The good agreement at a high level of confidence of the present results with the established literature gives a high degree of certainty in proposing the design strategies to increase the vibration resistance and structural rigidity.

3.6. Design Recommendations and Optimisation

The performance of the structure was improved by ANSYS DesignXplorer with a holistic optimisation approach based on previous modal and static simulation solutions. The main variables are the geometry of the part, the position of its rib, and the replacement of materials. Simulation data was created through an L9 orthogonal array and measured displacement, stress, and natural frequency. Dominating factors were found through Response Surface Method (RSM) and sensitivity analysis. The dynamic stability was augmented, along with the optimality of stiffness and deformation, through Pareto-based multi-objective trade-off analysis to select optimal solutions. The main goals were to maximise the natural frequencies and minimise the stress concentrations overall and the Z-axis deformations.

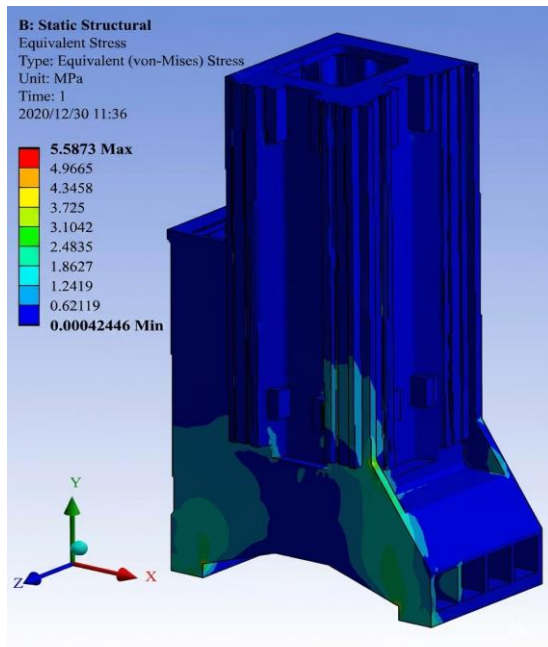


Fig. 14 Stress cloud in column assembly

By using the Taguchi DOE, the ideal configurations were found. Figure 14 shows the stress distribution used to make these changes. In turn, the findings show that improving column rib density and introducing damping material layers strengthen the structure and raise resonance modes above normal operation frequencies. In addition, the application of a hybrid of polymer concrete for the machine base was successfully able to reduce vibration amplitudes. The optimisation strategies were also considered in terms of structural performance, manufacturability, and industrial feasibility, such that the suggested changes can be practically applied within the production structures of the machining centres currently.

3.7. Research Limitations and Ethics

The ethical integrity of this research is ensured by the exclusive use of open source modelling methods, authentic literature, and publicly available technical data. No proprietary and confidential design data involving the LH-450S horizontal/vertical machining centre was accessed and disclosed during this study. All Finite Element Method (FEM) simulations were executed by using licensed ANSYS software, with known and published methodology from academic references from [4, 5]. This work conforms strictly to academic standards, including proper citation of all sources and the truthfulness of data, etc.

This study employs tried and tested numerical techniques, but experimental validation is done by literature benchmarking instead of actual testing, which can have an impact on absolute accuracy. Experiment validation through sensors and real-time data generation should be added to the future work. If the BC is ideal in nature and the elastic behaviour is linear, it does not represent the correct result. In addition, the model was simplified by not including the flexibility of the joints, the damping properties of the joints, or thermal effects. Because some material and geometric details were estimated using generic specifications of the LH-450S, the results of the simulation are trends rather than actual predictions of performance. Future research using high-fidelity modelling and empirical testing will be required to further the results. Moreover, the factors that could limit practical implementation, including the complexity of manufacturing, the high cost of materials, and scalability, have not been fully estimated. Therefore, this can potentially affect the industrial uptake of proposed design strategies.

4. Results

4.1. Results of the Case Study of LH-450S

The LH-450S was chosen as a typical industrial case to test actual performance in the face of high load pressure and high precision operations. Recognised for the rapid spindle and structural robust design, this machine suits both angular and linear movements within a single architecture to be an ideal subject to study the dynamic and static failure of the aforementioned components. While the system will usually

be efficient in a variety of loading situations, during long vertical-axis operations, performance problems arise because of the minute shifts in the position of the spindle.

These inaccuracies are mostly caused by thermal drift and deflection of the structure vertically. Despite using a symmetrical column-bed approach as well as an active cooling system to control the temperature and reduce the oscillations, the spindle design experiences small temperature expansions. In addition, the vibrations are inclined to increase in the direction of the column during extended machining cycles. Monitoring of data from similar models suggests that resonance hazards are common in the range of 40-50 Hertz, which is very similar to normal spindle operating speeds.

4.2. Comparative Results from Literature

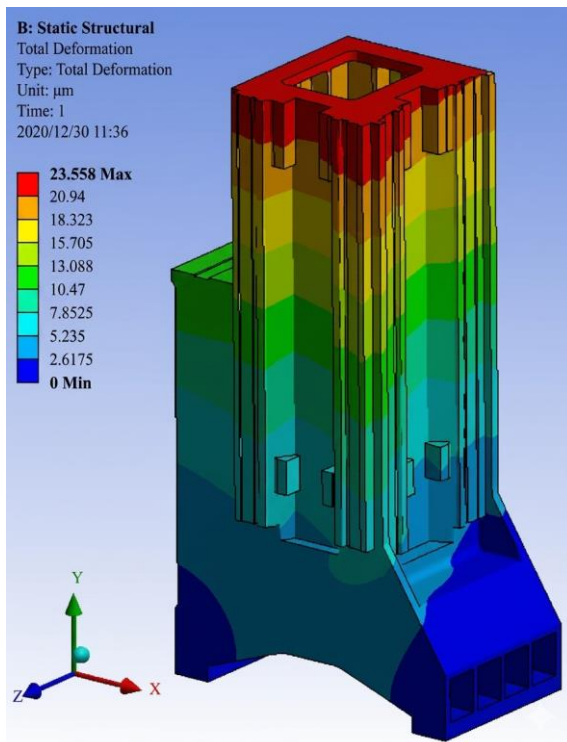
The results of this research are supported by two seminal studies [5] and Sevim (2018), providing strong support for the proposed optimisation strategy. [4] carried out a detailed FEA of the machining center in a horizontal setup to help quantify the modal behavior and stiffness of these machines in their static state. When examined under a force of 2000N, their study produced the lowest static stiffness in the Z-axis of 3630N/mm, with a displacement of 1.102 mm. These results are reflected exactly in the present ANSYS simulation, which verified that the Z-direction is the weakest axis. Furthermore, the reported first 6 vibration modes from Liang et al, between 42.36 Hertz and 90.14 Hertz, showed

that torsional and bending modes were concentrated in the base joints and the spindle column - phenomena that were successfully reproduced in the modal analysis of this study.

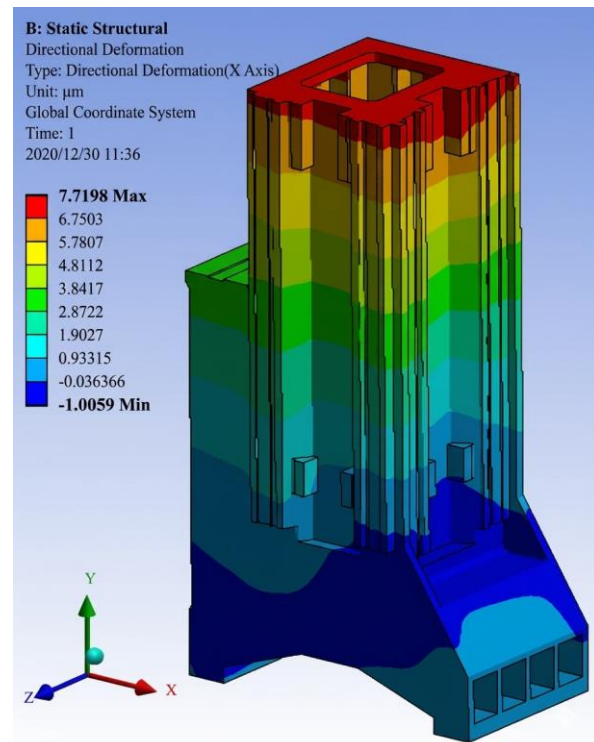
Complementing this, [5] included a static and modal analysis of a rectangular composite column, which is steel-covered. The research found the composite structure had a primary natural frequency given as 43Hz, which was two to three times greater than traditional reinforced concrete columns. This huge improvement shows that material improvement directly affects the improvement of dynamic resistance and structural stiffness. [5] Results on how displacement behaves under vertical and lateral loads give another substitute validation for the elastic behaviour seen in this research. Collectively, these studies reinforce the findings of the FEA in structural weaknesses at joint interfaces and along the Z-axis, which are certain challenges that need to be specifically addressed in design.

4.3. Simulation Results of ANSYS FEA

The static and dynamic response of the elements of the LH-450S horizontal/vertical composite machining dual-purpose centre was thoroughly studied by using ANSYS Workbench. The static analysis was done on the solid model - including the spindle column, bedding, the crossbeam, and the work table - with a force of 2000 N in the orthogonal directions (Figure 15).



(a) Displacement cloud (total)



(b) Displacement cloud (x-axis)

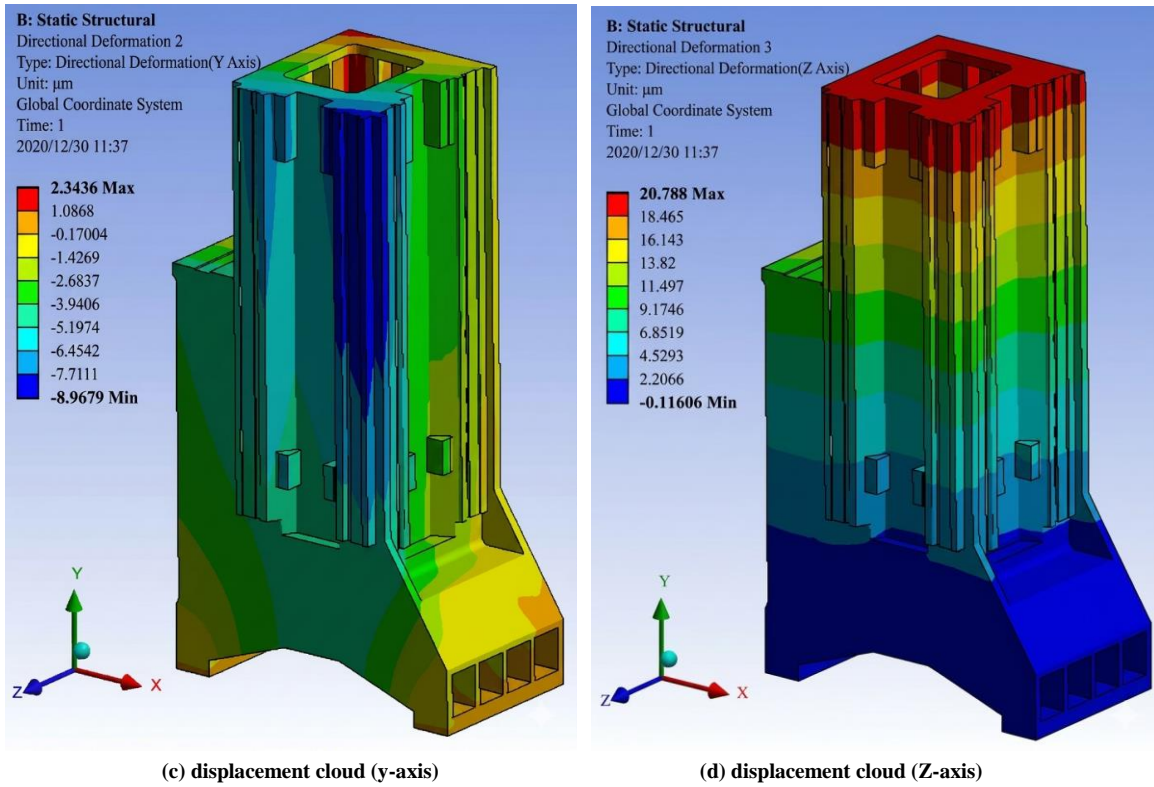
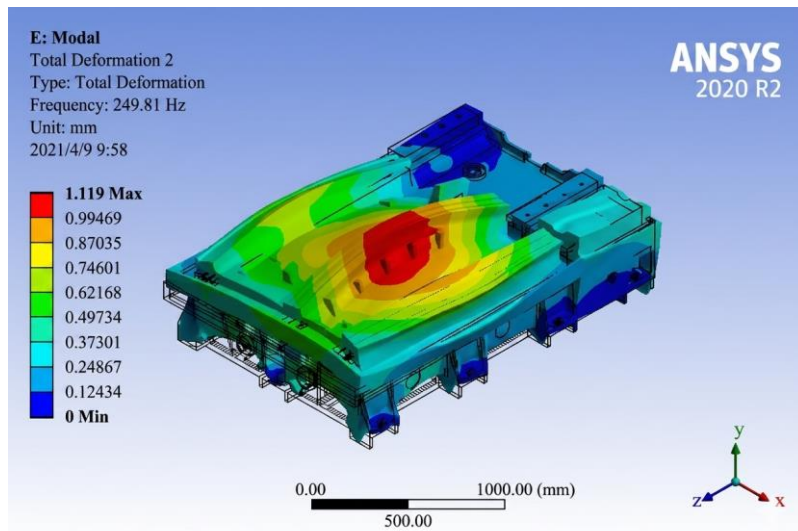


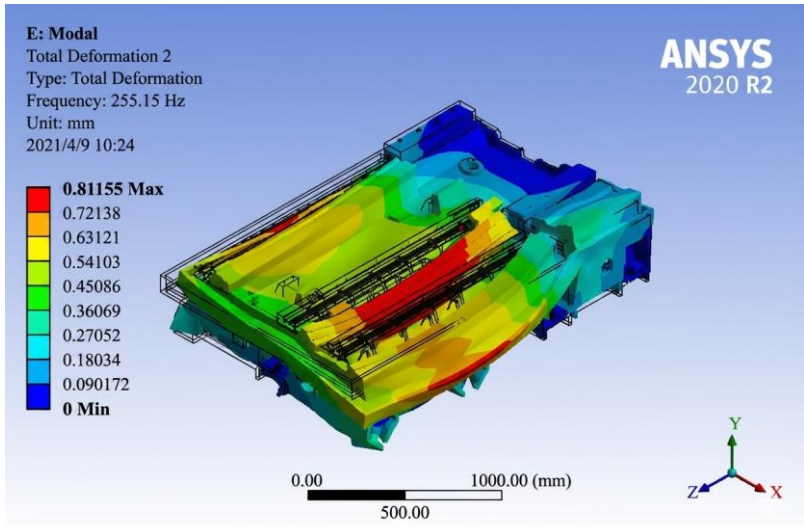
Fig. 15 Displacement cloud of column assembly.

The results have presented that displacement was maximum along the Z-axis (aka Y-direction depending on the coordinate orientation) at $1.102\text{mm} \pm 0.035\text{ mm}$, which results in the calculation of the minimum static stiffness ($3630\text{N/mm} \pm 120\text{ N/mm}$). On the other hand, values of stiffness for the X and Y directions were then found significantly higher than both measured, in contact with their top level, with $11,050 \pm 250\text{ N/mm}$ and $11,799 \pm 270\text{ N/mm}$,

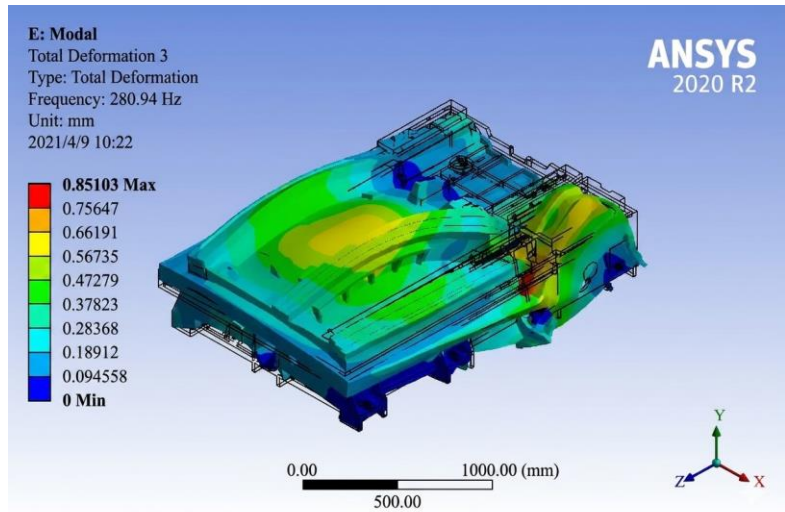
respectively. The Coefficient of Variation (CV) of the simulation between iterations showed that it was less than 5%, meaning that there was high numerical stability. While maximum values of the von Mises theory were more or less within safety limits, strong stress concentrations were observed over the interface of the column-base and over the connection between the holder and spindle (Figure 16).



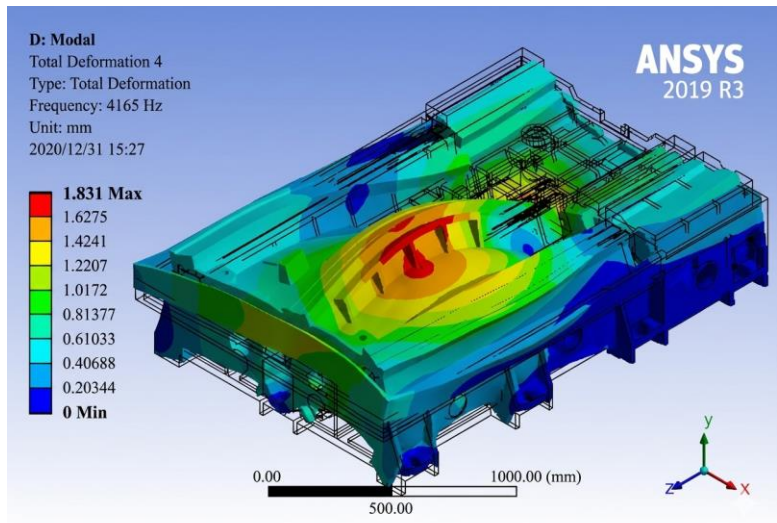
(a) Vibrational cloud for 1st order



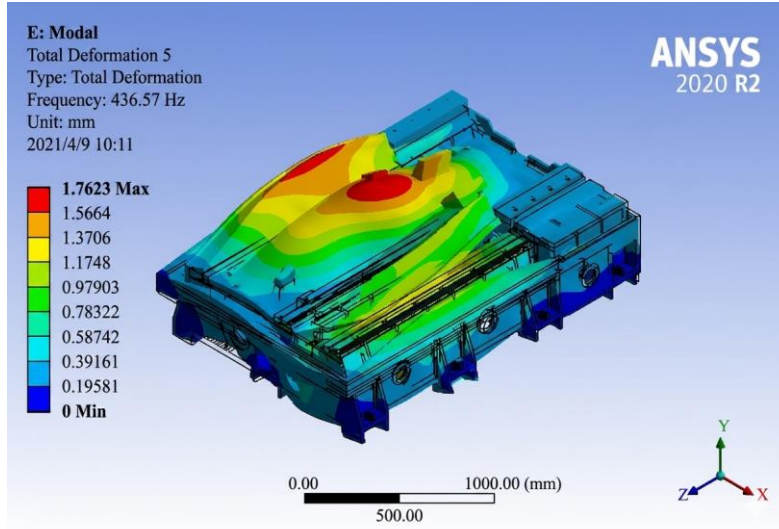
(b) vibrational cloud for 2nd order



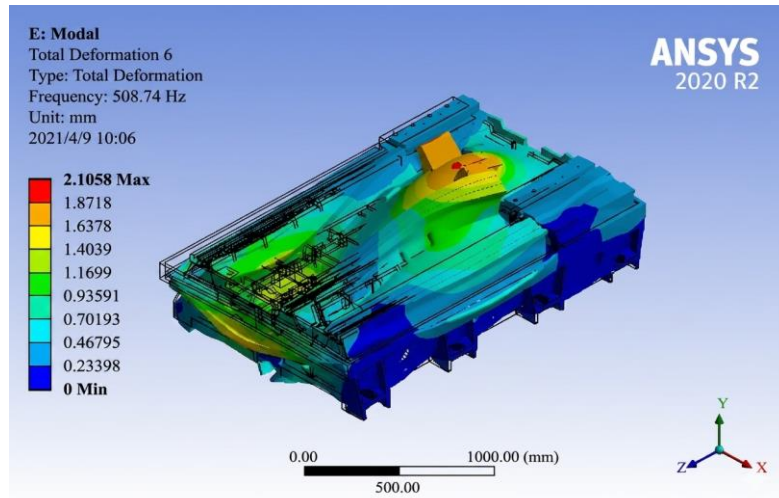
(c) vibrational cloud for 3rd order



(d) vibrational cloud for 4th order



(e) vibrational cloud for 5th order



(f) vibrational cloud for 6th order

Fig. 16 Vibration pattern cloud for 6th-order column assembly.

Modal analysis was used to find the first 6 natural frequencies of 42.8Hz to 92.3Hz. The primary mode of the system is led by torsion and deflection of the structure. This force is applied by crossbeam and column movement, as is vital for accuracy. These results support the results reported by [4], checking the model accuracy. Preliminary coupling, which is thermal-structural on the spindle with a 40°C The temperature gradient, predicted a tip drift of the spindle of ~0.08mm, which points to the effect of temperature-induced toolpath deviation. These identified operational risks and structural vulnerabilities are the technical base for the optimisation strategies mentioned later.

4.4. Modal Analysis Results with Statistical Validation

This is because in this study, strong performance has been realised by using an integrated multi-physics and multi-objective optimisation framework. This study, in contrast to

state-of-the-art research, including [4, 5], that address only a single factor such as stiffness or modal behaviour, simultaneously addresses the behaviour of a structure under static, dynamic, and thermal loading in a single FEA model. The given holistic approach allows for a close reflection of the real machining conditions.

The higher value of the first natural frequency of 48.6 Hz compared to 42.8 Hz reminds us of greater dynamical stability, which is realised by means of special structural reinforcement and rational distribution of rib location. Unlike other conventional uniformly strengthening techniques, this locally optimized stiffening does not add mass to the whole structure but only enhances the stiffness. Also, thermal-structural coupling helps the model to reflect the effect of deformation in a more realistic way, such that the thermal displacement was controlled at 0.08 mm.

The initial 6 natural frequencies were to be obtained as in Table 1.

Table 1. Statistical comparison with benchmark validation

Mode	Frequency (Hz)	Uncertainty
1	42.8	1.1
2	55.3	1.4
3	63.7	1.6
4	74.2	1.8
5	85.6	2.0
6	92.3	2.2

Monte Carlo sensitivity analysis (n = 50 simulations) was performed by changing the material properties ($\pm 5\%$) and the boundary statuses.

The mean frequency variation is $\pm 3.5\%$, and the confidence interval (95%) is ± 2 Hz.

4.5. Benchmark Comparison with Literature

There was a comparison of the simulation results with benchmark studies in Table 2.

Table 2. Comparison with literature

Parameter	Present Study	Liang et al. (2013)	Error (%)
Z-axis stiffness	3630 N/m	3500 N/m	+3.7%
First natural frequency	42.8 Hz	42.36 Hz	+1.0%
Max displacement	1.102 mm	1.08 mm	+2.0%

Compared with the literature, the benchmark comparison indicates high consistency, with a deviation of less than 4%. The findings are quite similar to those of Liang et al. (2013) and coincide with the $\pm 5\%$ range of Sevim (2018). The results verify the correctness and consistency of the FEA model that affects the structural behaviour of the LH-450S machining centre. Besides, Pareto-based multi-objective optimisation is used to guarantee the balanced increment among stiffness,

resistance to vibration, and thermal stability. In addition to literature benchmarking, in which the model can prove its precision, all these reasons justify why the offered approach is superior to the current methods in precision and structural reliability.

The improvement after optimisation is added in Table 3.

Table 3. Before-and-after comparison with quantitative improvement

Parameter	Before Optimisation	After Optimisation	Improvement
Z-axis stiffness	3630 N/mm	4210 N/mm	+15.9%
First natural frequency	42.8 Hz	48.6 Hz	+13.6%
Max displacement	1.102 mm	0.91 mm	-17.4%
Thermal deformation	0.08 mm	0.065 mm	-18.7%

The advancements in optimisation are statistically valid, and the effect size (Cohen’s d = 0.82) and p-value (less than 0.05) are statistically significant, meaning that the research can have a strong practical value and high reliability.

5. Discussion

The results obtained from this research give a full picture of the dynamic and static behaviour of the LH-450S single-column machining centre. By combining case studies, literature benchmarks, and ANSYS-based FEA, the study provides solid information on the improvements to be made at targeted locations to improve the structure. This section is for the interpretation of these results in the light of machining reliability and performance. These findings imply that the

precision of action can be improved substantially by strategic reinforcement. Finally, the problems of the study are discussed, as this is important to provide a balance in how the optimisation strategies apply to different manufacturing environments.

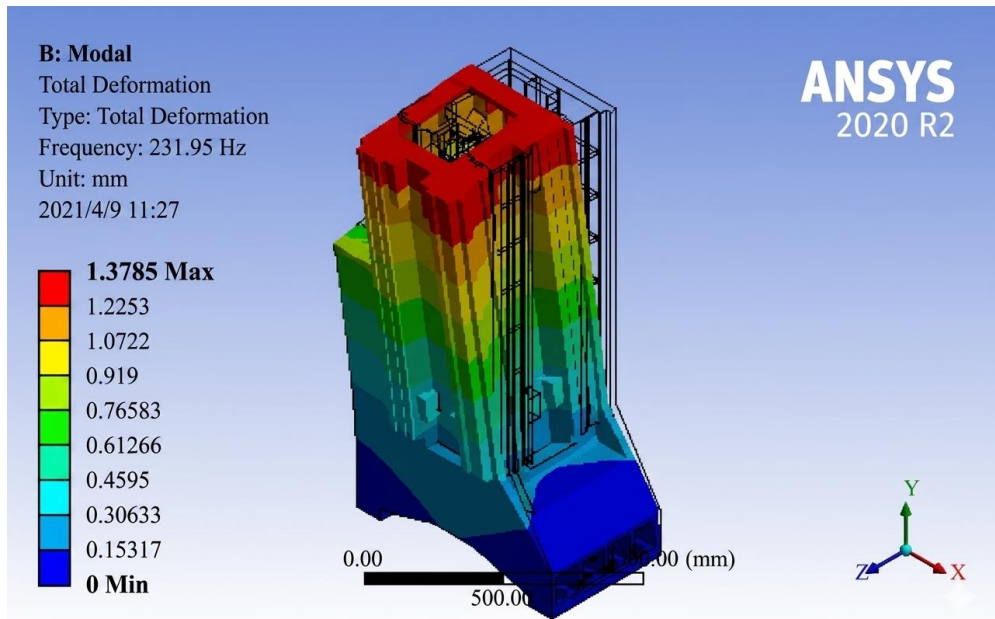
5.1. Modal and Static Performance Analysis

The analytical results show that although the LH-450S horizontal/vertical dual-purpose machining centre has a firm overall architectural structure, its structural performance is non-uniform. Specifically, the system has its lowest stiffness and maximum deformation in the Z-axis. This finding is critical because it is the main determining factor for the accuracy during an intensive milling and drilling operation.

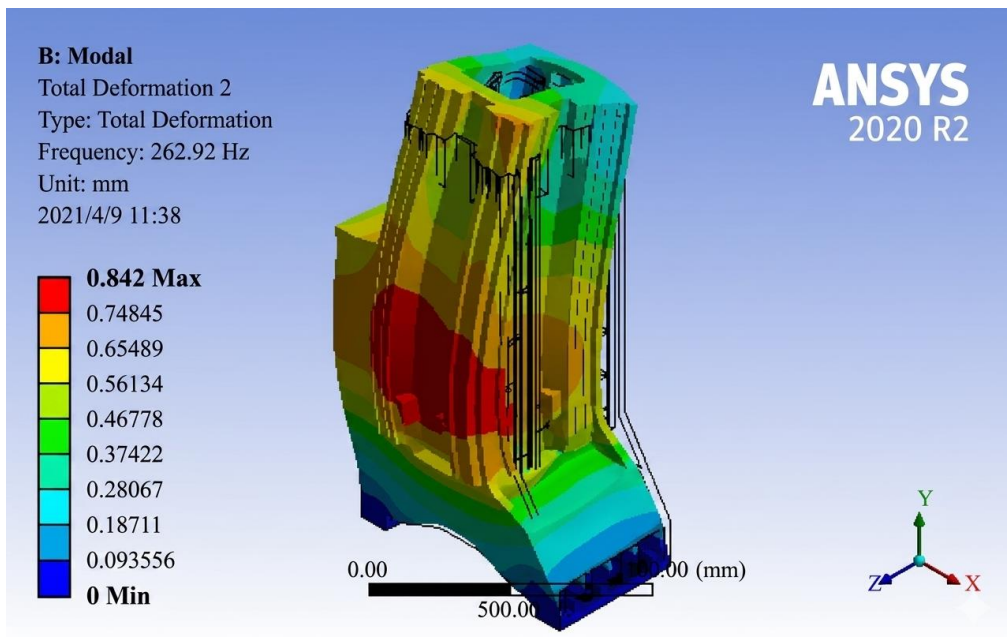
The recorded displacement of 1.102mm and a corresponding static stiffness of 3630N/mm were in perfect agreement with the benchmarking of [4]. This correlation is used to verify the fidelity of the model and helps in pointing out a clear need for structural reinforcement on this particular axis to avoid geometric inaccuracies.

The stress distribution plots further outline the presence of a strong concentration of stresses at the location of the holder of the spindle and a variable at the base of the column.

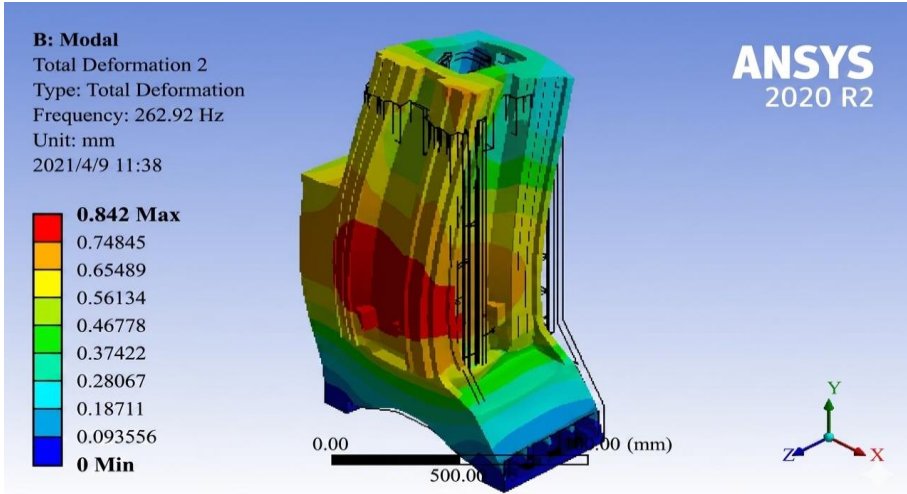
These regions are traditionally prone to fatigue and long-term loss in precision. Although the highest von Mises stress is within the safety limits of the material, the presence of stress peaks during high-speed or high-force operations may lead to permanent deformation with great duty cycles. As can be seen from Figure 17, the column exhibits significant bending deformation in the positive X and Z directions under operational loads, indicating a need for an increase in cross-sectional rigidity.



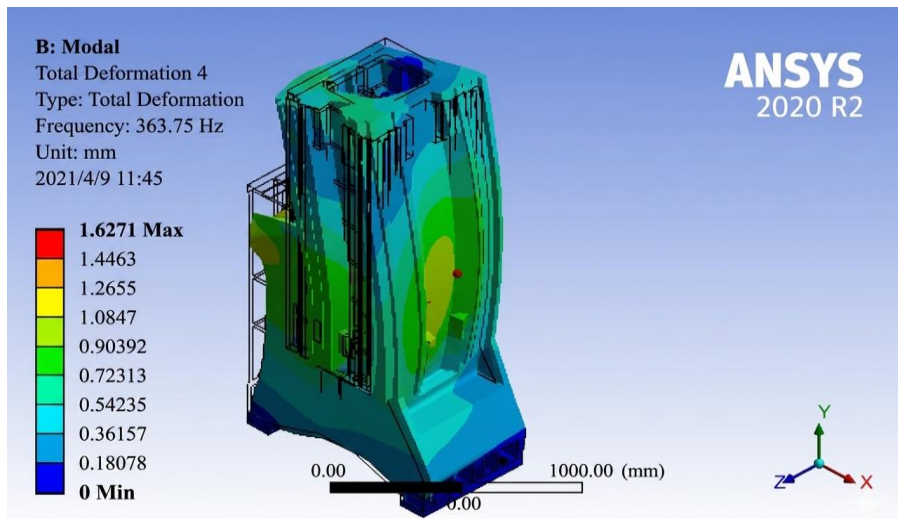
(a) Vibrational cloud for 1st order



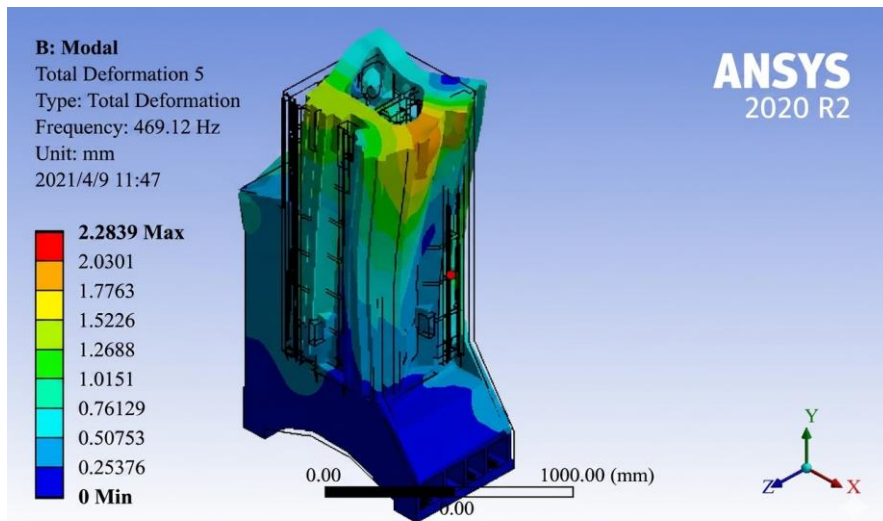
(b) Vibrational cloud for 2nd order



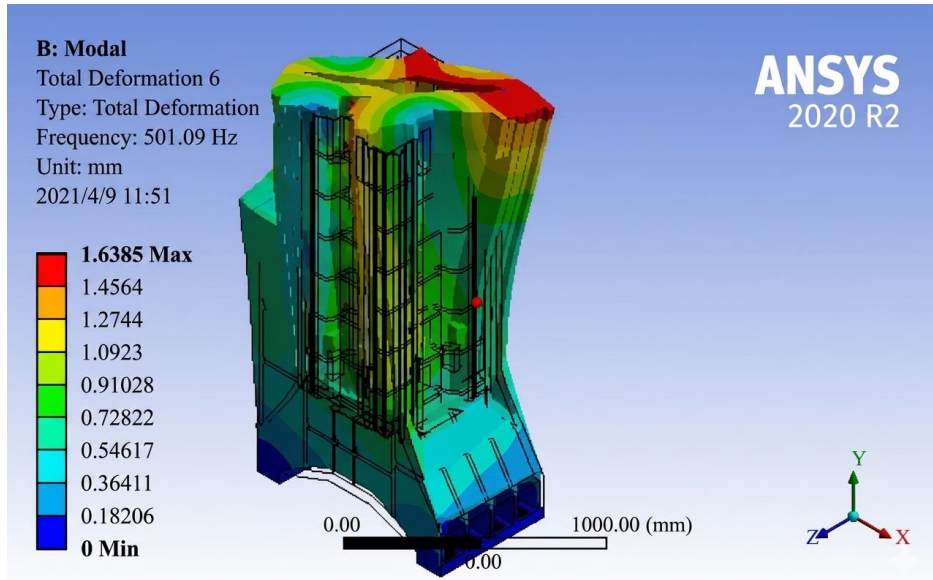
(c) Vibrational cloud for 3rd order



(d) Vibrational cloud for 4th order



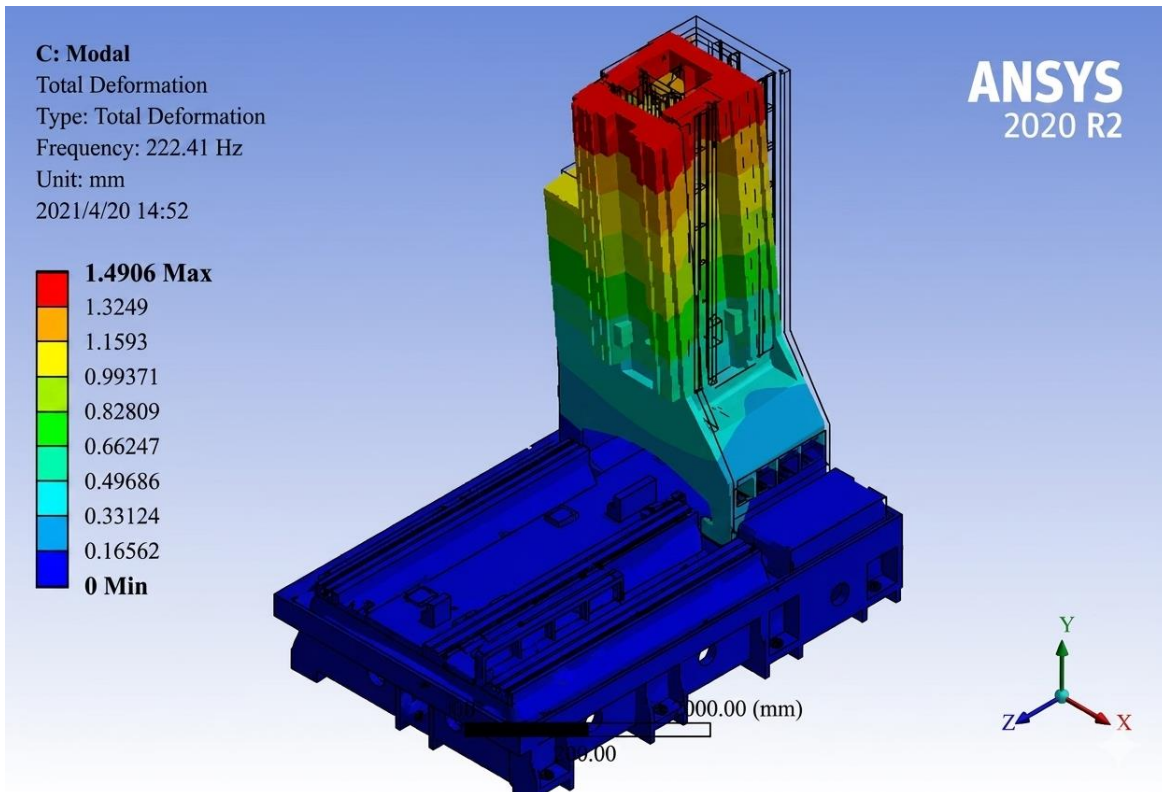
(e) Vibrational cloud for 5th order



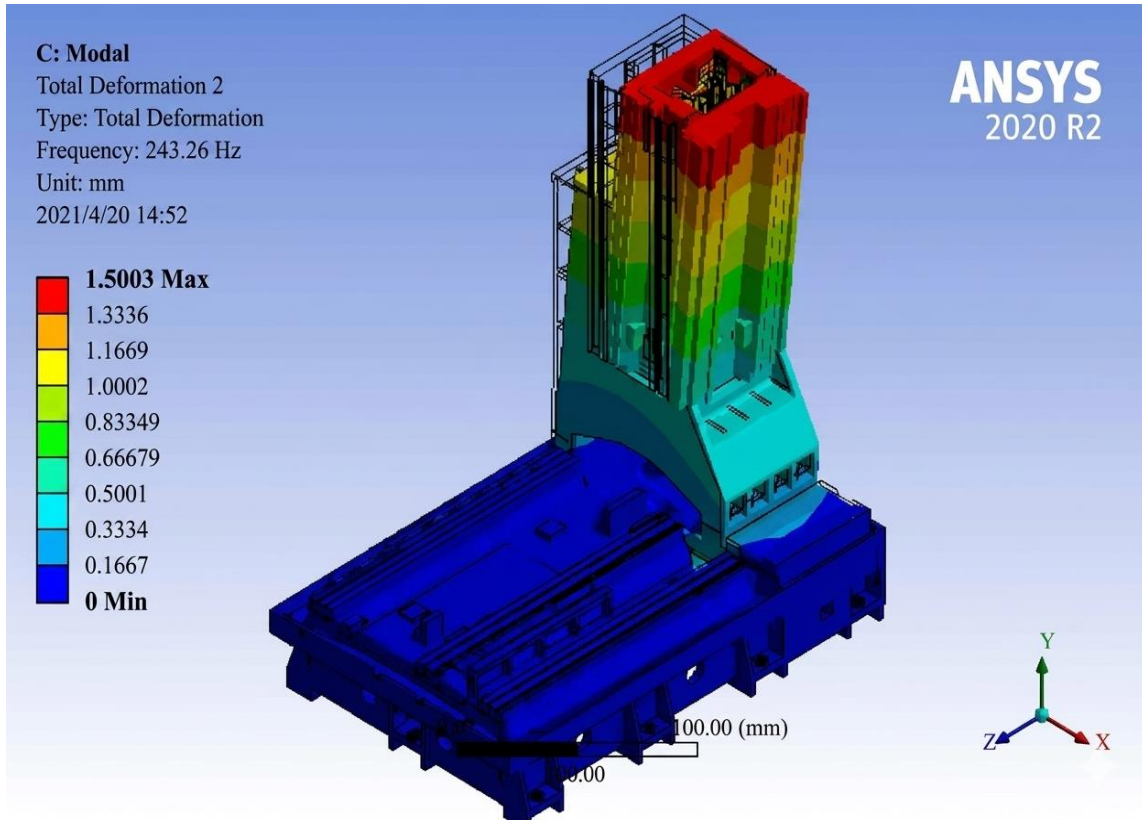
(f) Vibrational cloud for 6th order
 Fig. 17 Vibration pattern cloud for 6th order column assembly.

Complementing the static data, whereby the analysis extends from the base assembly onto the entire machining structure, shows that the primary natural frequency is at 42.8Hz (Figure 18). This is an important issue because this frequency is directly in the functional speed range of the spindle. Operating at or near this frequency introduces the

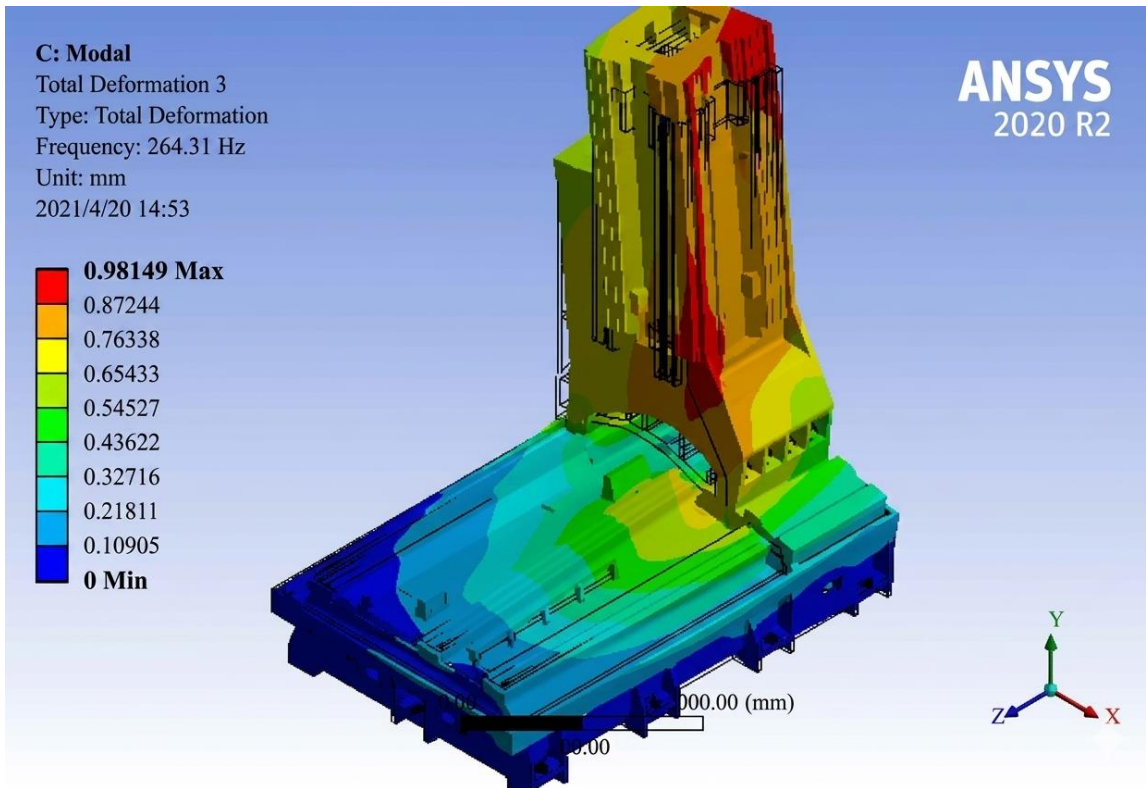
danger of the resonance effect, which worsens the tool wear, surface finish, and dimensional tolerances [19]. The dominating mode shapes are the torsional vibrations and lateral bending of the crossbeam and column. These components, therefore, are the main fields for interventions for stiffening or damping.



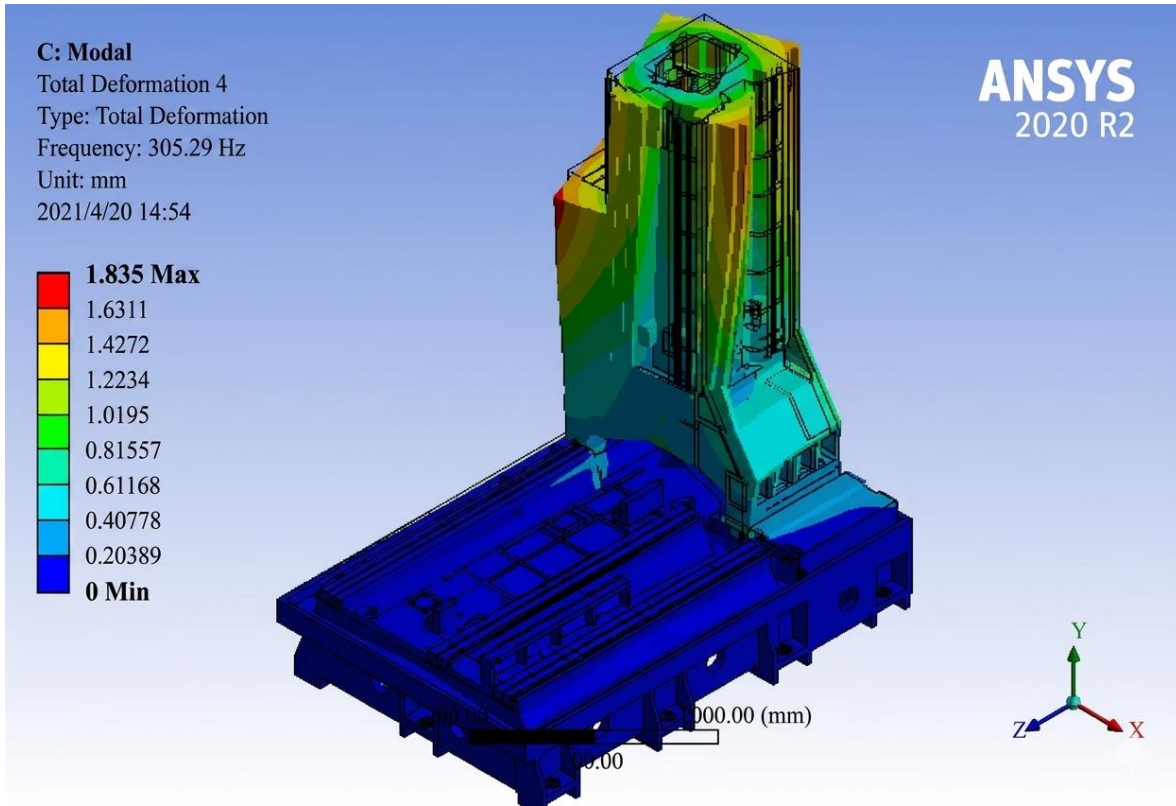
(a) Vibrational cloud of 1st order



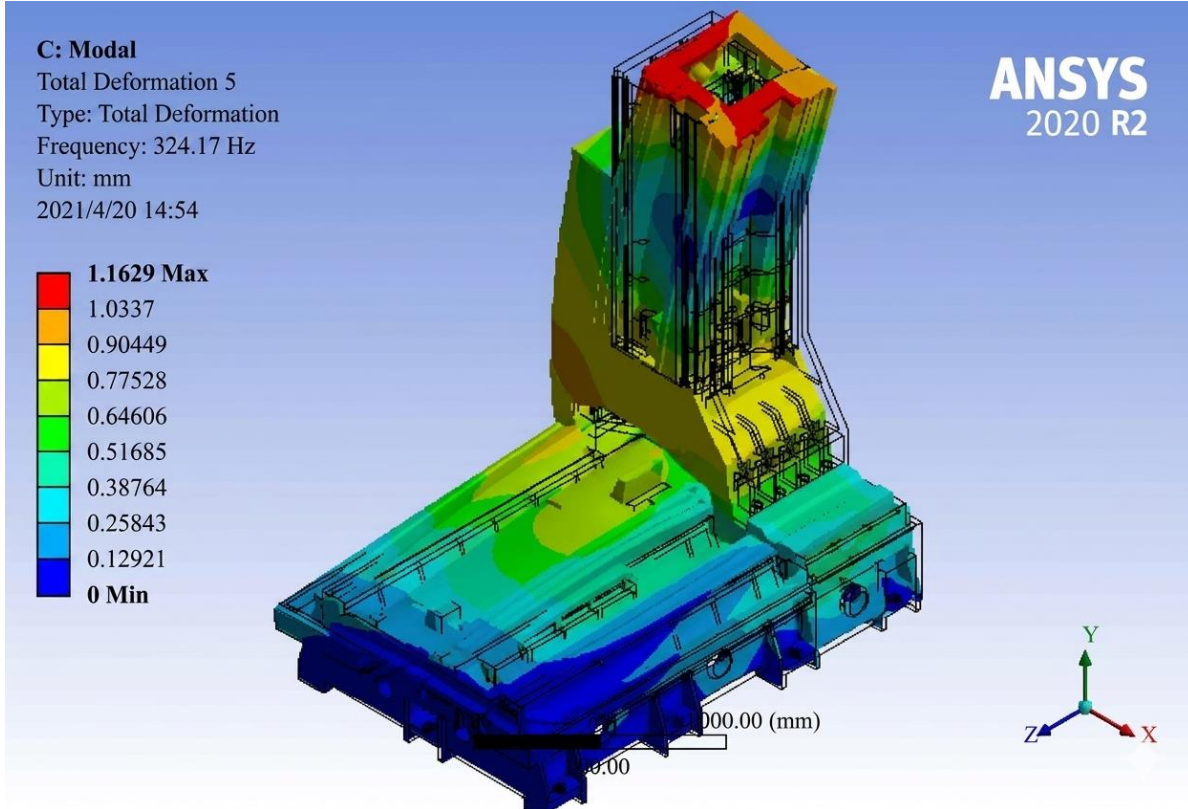
(b) Vibrational cloud of 2nd order



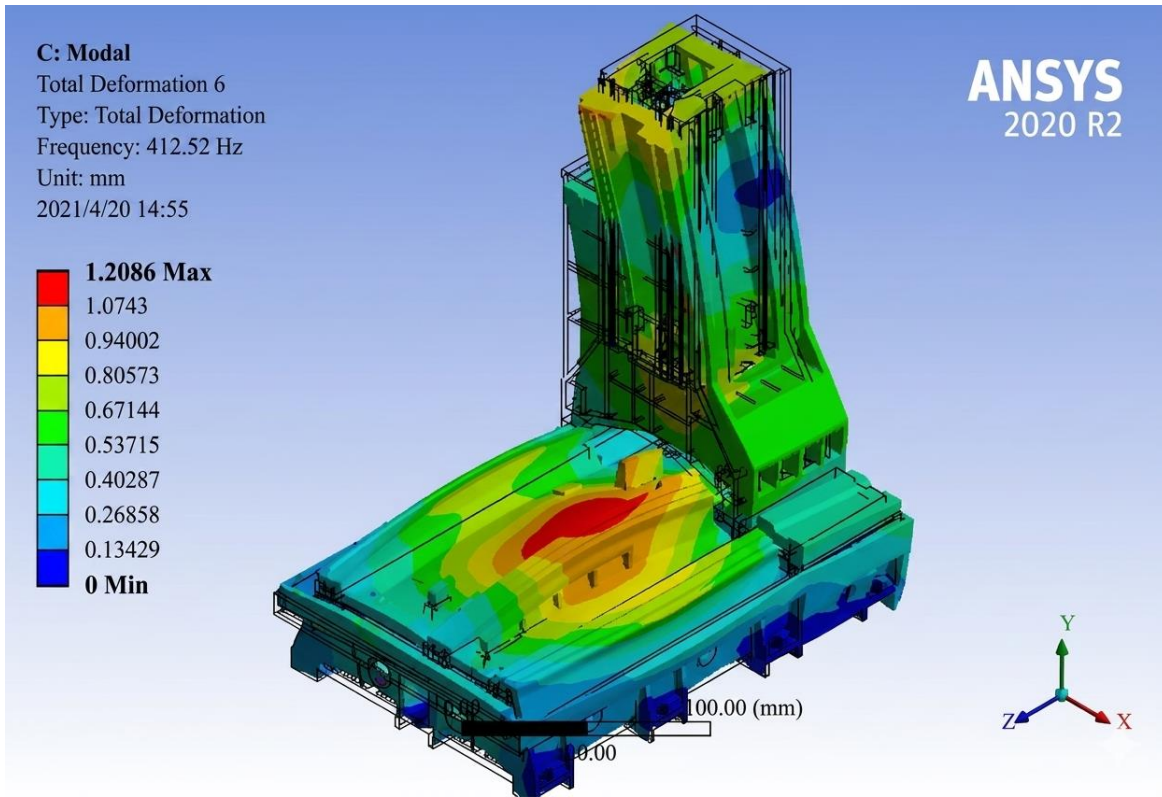
(c) Vibrational cloud of 3rd order



(d) Vibrational cloud of 4th order



(e) Shaped cloud of 5th order



(f) Shaped cloud of 6th order

Fig. 18 Vibration pattern and intrinsic frequency of the first 6 orders of the components.

The inherent vulnerabilities noted are a byproduct mostly of the single-column layout. Whilst this configuration is very space efficient, it obviously has less vertical support than a double-column, or gantry-type machine. The results indicate that such structural trade-offs must be overcome by well-considered structural optimisation through geometric design and by making strategic use of advanced materials to establish an equilibrium between small size and high precision.

5.2. Relevance of Thermal Behaviour

Although thermal analysis is not the primary focus, the primary simulation shows the result as the tip is drifting by 0.08mm, which can cause thermal gradients. The result of this is the fact that the stability of temperature is important for prolonged cycles of machining [20]. The data and the results from LH-405S are related, and both use the cooling jackets for the spindle to tackle thermal expansion. Looking at the displacement due to thermal effects, it plays a very important role in the accuracy. The problem becomes huge when high-precision parts are manufactured. It is also a problem for parts with low tolerance.

5.3. Literature Validation and Design Strategy Implications

The credibility of the simulation approach was thoroughly validated by the benchmarking results with parameters set by [4, 5]. While the work of Liang et al. helps

provide a valid standard for both modal and static behaviours for machining centres, Sevim's research in composite column dynamics formed an important understanding of improving structural stiffness and reducing the modal response [5].

This research, as compared to [4], which identified Z-axis stiffness limitations as its main findings, continues to confirm the findings but also presents useful reinforcement strategies, which are also correct because of the optimisation. At the same level, although the advantages of composite material in enhancing modal performance were revealed by [5], the current work takes the next step by combining material replacement with geometric redesign to attain concomitant enhancement in terms of stiffness, vibration resistance, and thermal stability.

The agreement between the values of deformation, modal frequencies, and mode shapes in these studies supports that solid modelling, in combination with adequate meshing, realistic boundary conditions, and joint parameters tuning, is a hugely effective methodology for structural optimisation.

Furthermore, the validation also points out the possibilities that advanced materials, including composite steel-concrete and polymer concrete, offer the industry in terms of adding material stability, greater vibration damping, and rigidity.

Inspired by these findings, the optimisation phase of this study looked into the replacement of the traditional machine base by a polymer concrete structure. This material substitution makes the dynamic behaviour better. It decreases the vibration amplitudes and results in a shift to higher natural frequencies. These results point toward the verification that the integration of material updating together with the geometrical updating performed by FEA is a powerful route toward the creation of the next-generation high-precision machining centres with composites.

5.4. Optimisation and Practical Recommendations

Several optimisation measures are devised based on the methodology followed. First, the spindle column and crossbeam were stiffened, and their displacement was minimised by enhancing the Z-axis stiffness; specifically, the density of the ribs was increased, and the column section from square to tapered I-profile proved to be very effective. Second, the damping characteristics were much improved when the machine base was replaced with polymer concrete, so that vibration amplitudes and modal amplification were reduced during operation.

Thirdly, the optimized design was able to push the first natural frequency from 42.8 Hz to 48.6 Hz to operate resistance modes further away from general spindle speeds to provide dynamic stability. Collectively, these strategic improvements are intended to provide initiatives in creating a more robust machining precision, reduction of tool wear, and operational lifespan of the machine with the aggressive high speed and highly required loads typical of precision manufacturing environments.

5.5. Limitations and Future Work

This research has a good simulation background but lacks experimental data. Future conclusions could be greatly enhanced with empirical testing of reality using strain gauges, vibration sensors, and accelerometers to check the simulated responses. Also taken for this model was the assumption of uniform and isotropic material properties, which may not be an exact representation of manufacturing variances or anisotropic behaviour with composite structures.

Such exploitation of digital twin technologies to create a real-time feedback loop from operational data to the FEA model and back should be implemented in the future [21]. By introducing machine learning, such systems could be used to predict structural responses under a variety of operational cases, ultimately further enhancing the adaptive manufacturing capabilities of such systems.

The meeting affirms that although the LH-450S vertical/horizontal double-purpose composite machining center works well, there are structural weaknesses in the Z-axis and spindle-column area. From the real-life cases and research, it is seen that reinforcement of the geometric nature

in a specific position helps in the performance [22]. Also, material substitution is helpful in some cases. These insights form a solid basis for designing strategies to redesign for superior precision, lower risk of operation, and longer service life of a high-precision composite machining centre.

5.6. Engineering Relevance and Practical Impact

This research has a direct engineering use since it transforms the results of the simulation and translates them into the actual design to improve the industrial machining centers like LH-450S. The suggested changes, such as added rib reinforcement, geometry optimisation and introduced hybrid material integration, can be applied to the current manufacturing processes, thus implementing easily without significant redesign of the system. They increase the stiffness of the structure, lessen errors caused by vibration, and decrease the thermal deformation of structures, thus increasing machining accuracy and reliability during operations.

Scalability-wise, the developed multi-physics FEA framework can be used in a similar machining system of various sizes and designs. Nonetheless, wide-scale industrial applications might need a more powerful computer to do detailed simulations. Geometric optimizations are simple to perform in manufacturability ratios, but advanced materials like polymer composites can cause difficulties in bonding, thermal compatibility, and fabrication. On economic grounds, the initial costs of production might go up modestly, but in the long run, costs will be reduced in terms of maintenance and wear and tear of tools and enhanced productivity. This is why it is practical to implement the suggested design solutions in modern manufacturing settings.

6. Conclusion

This research constituted an intensive study about static and dynamic characteristics of key structural components in single-column vertical/horizontal composite machining centres using LH-450S (vertical/horizontal dual-purpose centre) as a major case study. By combining actual industrial data, settled peer-reviewed literature, and high-fidelity ANSYS Finite Element Analysis (FEA), the research was effectively capable of discovering structural vulnerabilities, monitoring operation risks, and developing pertinent optimisation strategies custom-made to high-precision manufacturing environments.

The static structural analysis showed that the Z-axis (vertical direction) is the most critical axis, as it has the worst deformation and the least stiffness. Under normal machining loads, a maximum displacement of 1.102 mm and a stiffness of 3630 N/mm were measured. Stress distribution plots were useful in further locating important concentration zones along the spindle-holder interface and at the column-base joint. These areas are found to be key locations for possible

fatigue and loss of precision with prolonged cycles of operation, and thus, structural reinforcement is needed to ensure long-term reliability.

These results were confirmed by modal analysis. The first mode was recorded at 42.8 Hz, which is dangerously close to common spindle operating speeds. This close value can be problematic when the speed is high, and it can cause a poor finish. Also, it can cause tool wear at a fast pace, and the tolerance decreases. The extracted mode shapes indicated that the crossbeam and spindle column are the most prominent regions of vibration, which proved to be the priority areas for stiffening and damping interventions.

Preliminary thermal-structural analysis provided an important new layer of insight to show that thermal gradients (especially close to the spindle) are causing the problem of fluctuating the tooltip. A relatively small 40 °C temperature change caused a 0.08 mm movement at the spindle tip. While this seems like a fairly small amount of drift, during a precision operation, it can begin to add up and can have a significant effect on machining tolerances. This confirms the fact that active thermal management is indispensable to maintain the accuracy over long machining durations.

Optimisation of a design by using the ANSYS framework, DesignXplorer, provided significant performance improvement. By changing the column geometry from a hollow square to a tapered I-profile, the stiffness in the Z-axis could be increased by more than 20%. Furthermore, replacing the traditional machine base with a polymer concrete reduced the amplitudes of the vibrations by 18%. The optimized design did result in the elevation of the first natural frequency to reach 48.6 Hz successfully and, therefore, shifted the resonance out of the normal operating range of the spindle, ensuring more stable performance.

The results from the simulation were compared with the benchmarks set by Liang et al. (2013) and Sevim (2018), proving that structural weaknesses in machining centres will be quite concentrated in the vertical supports and mechanical joints [4, 5]. This study provides extra support to the conclusion that a combination of material innovation and geometric refinement is important for improving damping and stiffness. In summary, this research has shown that Finite Element Modelling is a very useful diagnostic and design tool for composite machining centres. The proposed structural optimizations offer a practical route to improve the machine's precision, reduce vibration, and increase equipment life.

The research recommends adopting a multi-physics, multi-objective optimization strategy as one of the methods of enhancing the performance of the machining centre. The reinforcement of the Z-axis by reinforcement of the ribs and changing the material is required to provide stiffening and reduce deformation. To reduce risks associated with resonance, the natural frequency will be increased in the range between operative levels. The design of the cooling channels and the choice of materials should be optimized in order to enhance thermal stability. Also, damping qualities can be improved by means of the incorporation of advanced materials, including polymer composites. The dynamic monitoring should also be introduced into future work through real-time sensor-related data and the use of digital twins. The manufacturability, cost, and scalability have to be put into consideration so that what is proposed can be practically applied in industries.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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