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Experimental and Numerical Analysis for Safe Measurement Location on M544 CMM Working Table

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ABSTRACT

A coordinate Measuring Machine (CMM) is a more flexible, adaptive, and precise dimensional measuring machine. Being a complicated measuring tool, CMMs can have a wide range of error sources that can lower measurement accuracy and increase measurement result uncertainty. Mapping and compensation techniques are commonly used to minimize measurement error in CMMs. However, the aforesaid techniques require resources and expertise. An alternate and less costly method of lowering CMM measurement error is to measure at its working table's smallest moving structural static deformation site. By looking at the CMM structure's stress and deformation using FEA, CMM measurement error can be reduced. In this paper, experimental and numerical analyses were used to determine the safe measurement site with minimum CMM measurement error on the CMM working table by analyzing the moving structural model. Based on the dispersed sample, the measurement plan was put into practice, and real measured samples were gathered using the Osmania University, Metrology Lab M544 CMM to validate the simulation. In addition, sensitivity analysis of the FEA simulation was conducted in relation to the key variables to confirm its robustness. The larger form error with the maximum measurement error was observed at the right end position of the ram and Z-shaft of the bridge type M544 CMM. The M544 CMM's right end (500, 0, 0) had a measurement error of 0.466 µmm due to the structural deflection, while the home position (0, 400, 0) had a measurement error of 0.146 µmm. The FEA static structural deformation result was in good agreement with the experiment. The safest place to take CMM measurements with the least measurement error is, at the middle 150 mm offset from the border of the rectangular granite-working table. This finding could support the manufacturing industry to reduce M544 CMMs' measurement errors during inspection.

Keywords: CMM, Static Deformation, FEA, Contact Measurement, Numerical analysis.

1. INTRODUCTION

The machine's performance of manufacturing industries still has to be improved due to stringent quality standards and competitive global market (Karim et al., 2008). In the manufacturing and academic sector, CMM is the vital measuring machine to check dimensional and geometrical information (Ferit, 2022). This machine is a combination of different structures and systems. These main component structures and sub-main systems contribute to measurement error in the final

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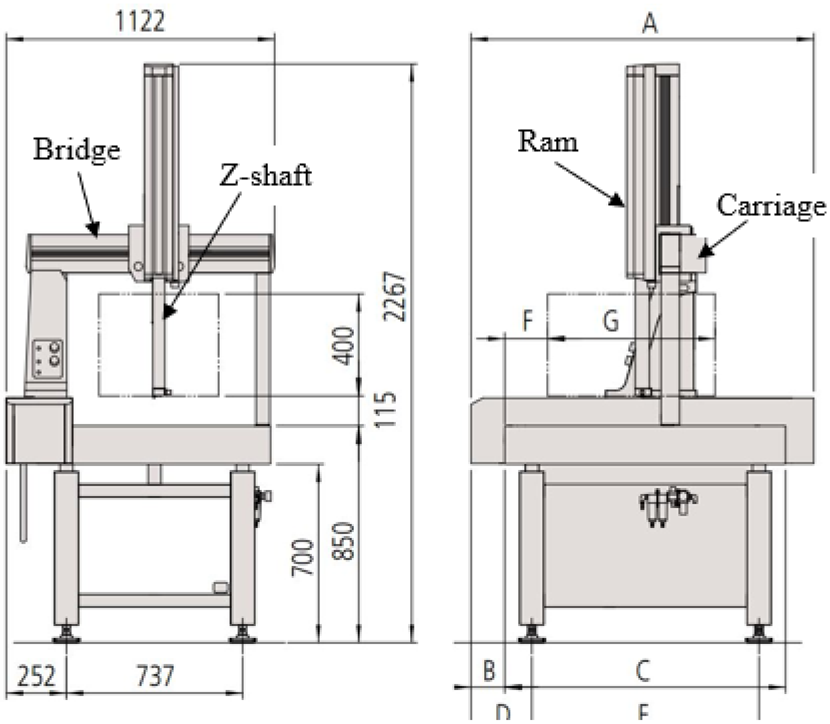
result (Barakat et al., 2000), particularly, to the part to be measured, working table, and the axis displacement (Jodar and Franco, 2024). Moreover, there are additional potential reasons of this kind of static geometric displacement, including the thermal effect (Jia et al., 2022), vibrational effect (Claverley and Leach, 2010; Wu et al., 2020), dynamic effect (Jodar and Franco, 2024), etc.

Understanding the stress concentration and the maximum deflection of the CMM geometric structure helps the company to compensate for the measurement error. Researchers have adopted geometric error compensation through calibration to incorporate the systematic error (Calvo et al., 2016; Lin and Hsieh, 2023; Pan et al., 2017; Teleshevskii and Sokolov, 2017). However, this technique is costly and needs expertise to conduct position error mapping and compensation (Zhang et al., 2024). Moreover, the ISO GUM (JCGM, 2020) introduces supplement guidelines to incorporate the simulation techniques of CMM uncertainty analysis. Nowadays, simulation based uncertainty analysis has become very popular even though they have limitations of assumption for complex systems and long implementation procedures (Locci et al., 2002; Gąska et al., 2017).

The numerical analysis can be utilized to determine the location of measurement with less CMM measurement error, even though they have limitations of idealized condition, oversimplification, trade-off model complexity, and human error (Aggogeri et al. 2011; Marjanovic et al. 2023). While there is not much similar information available to this work, the following have related concepts. Using the coordinate measuring machine model and the transformation matrix of the measured sample points, Zhang et al. (1985) created the error compensation model for CMM, which allowed for a reduction in measurement error. Yan et al. (2010) uses PRO/E software to model three-dimensional model of the CMM. The researchers use FEA to optimize the design component. They improved the CMM's strength in comparison to earlier CMMs. Chan et al. (2021) employed methods including FEA for transient investigations, modal, spectral, and static deformation. Using the CMM spatial measurement technique, they discovered that the moving structure of the measuring machine results in structural deformation and spatial geometric errors mapping. They then made the necessary adjustments to improve the machine's measurement accuracy. Chen et al. (2022) examined the relationship between the volume error and the geometric error of the CMM using a quasi-rigid body model. The precise location of the CMM measurement point was ascertained by utilizing the Levenberg Marquardt method in conjunction with the global positioning system localization principle. Their experimental findings demonstrated that the CMM's measurement accuracy improves with adjustment.

Consequently, much of the work discussed above focused on the CMM's measurement error mapping and compensation through an examination of the moving structural simulation. Unfortunately, the relationship between CMM measurement inaccuracy on the working table and structural low stiffness is not well studied. The CMM's structureexhibit flexibility under load, resulting in deformations that affect the accuracy of measurements at specific positions (Portman et al. 2015). This study presents M544 CMM measurement error minimization using virtual model simulation of the M544 CMM built in Solid works 2023. The carriage and Z-axis shaft (moving structure) as shown in figure 1 was simulated to determine the static moving structure deformation model and assess the safe site for measurement on the working table with minimal overall measurement error.



Specification: CMM Crysta-Plus M544(mm)	A	B	C	D	E	F	G
	1099	106	875	220	650	180	400

Figure 1. Dimension of M544 CMM (Mitutoyo, 2017).

2. METHODOLOGY

The National Physical laboratory (NPL), UK developed a Good Practice Guide No. 41(Flack, 2014), and the guideline elaborates technique steps of preparation includes part setup and probe alignment, followed by probe movement and data collection. The gathered data are analyzed and report is produced as per the specific GD &T requirement. These procedures were adopted to conduct measurement of the spatial flat bed. The novel and customized approach as shown in figure 2 was used to complete the work. FEA stress and deformation study of the M544 CMM structures were prepared using AutoCAD Mechanical 2016. The virtual twin of M544 CMM as shown in figure 1 was developed using Solid Works 2023 software. The result of FEA was validated with the actual measurement using M544 CMM (Metrology laboratory of the Mechanical Engineering Department at Osmania University, Telangana State, India). Prior to actual measurement, the CMM overall error was quantified through calibration of the master ball as per the guideline of the CMM manufacturer. Actual measurement was carried out after the machine soaked in the insulated metrology laboratory for nearly four hours, and the room temperature errors were maintained using the preinstalled A/C. Moreover, the machine has pre-installed thermal compensation software, and temperature variation other than 20^{0}C has been compensated as per the ISO 10360(2009(en)). The machine's overall measurement error was investigated using the flatness of the CMM's granite bed. To this effect, 121(11 samples along the x-axis, and 11 samples along the y-axis) discreet samples were measured using equi-parametric sampling strategy (Goitom and Rega, 2019) on 03/06/2024 at 10:53A.M.These samples were collected from the horizontal working table using the automatic measurement mode to reduce error due to operator. At the end, comparison of both experimentally measured flatness error and the CMM static deformation was performed, to investigate the safe location of measurement on the granite-working table.

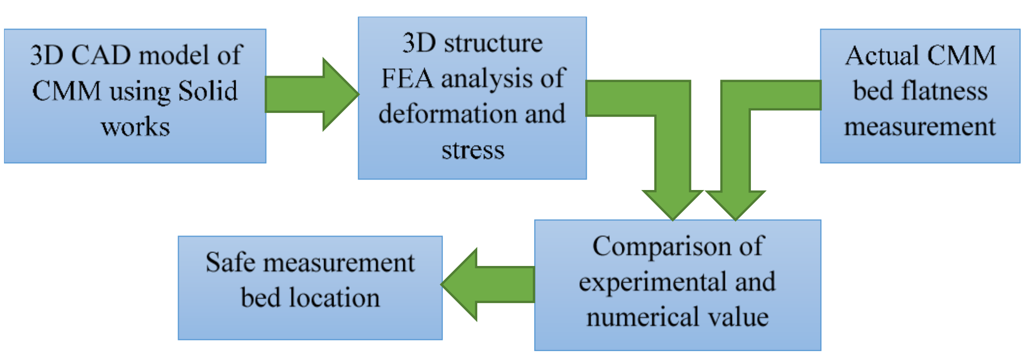


Figure 2. Overview of the approach.

2.1. CMM M544 Structural Simulation

Actual CMM digital represenation of of M544 CMM model with volumetric proportions of 3.082x10-4 m^3, density of 8000 kg/m^3, mass of 2.46 kg, and weight of 24.16N was created using Solidworks 2023. Mechanical AutoCAD 2016 was employed to conduct FEM CMM structure static simulation using Lenovo Laptop, and 8GB RAM. The weight of the moving structures were used to evaluate the Von Mess stress and deformation. The simulation was done at three different positions at home as shown in figure 3(a), middle of the crossbar as shown in figure 3(b), and at the right side of the home position as shown in figure 3(c). These position were chosen such that, in comparison to the middle stable position, the positions on the right and at home are more likely to have high bending moments (Eugen and Grupp, 1997). The model was designed for ascale of 1:100. The bridge load was distributed on the crossbar and the concentrated load of the Z-axis shaft at three different locations wereconsidered. According to the M544 CMM's design handbook (Mitutoyo, 2017), the main unit weighs 450 kg, stand weighed 62 kg, the granite bed 300 kg, the bridge 30 kg, and the Z-shaft is anticipated to be 20 kg. The analysis of structural stress and deformations were done based on these mass and dimensions. The bridge and the Z-axis shaft weight were considered as 50 kg over 100mm of the crossbar as shown in Figure 3. For five minutes, a triangular mesh with 13,427 nodes, 8,306 elements, and 40,281 DOF was examined.The FFEPlus solver type was utilized to do the numerical analysis on a static solid mesh at 298 Kelvin, which is the zero stain temperature. The CMM manufacturer guide of model-type linear elastic isotropic was followed in the arrangement of material portions to simulate the structure for AISI 321 Annealed Stainless Steel (SS) CMM body. The default criteria considered for failure was the maximum Von Mises stress. In this study, the following M544 CMM moving structural material(bridge + Z-shaft) properties were taken into account: mass density of 8000 kg/m^3, yield strength of 234MPa, tensile strength of 620MPa, elastic modulus of 1.93GPa, and thermal expansion coefficient of 0.017µmm /Kelvin as per the Mitutoyo user manual material charcterstics (Mitutoyo, 2017). As seen in figure 4, a roller/slider type of fixture at the airbearing site was utilized for a loaded kind of displacement (direct transfer) in red. Moreover, the machine condition was matched to the actual machine home position using global cartesian coordinates.

2.1.1. Sensitivity Analysis of M544 CMM Deflection Simulation

Model robustness and dependability under various situations can be revealed by using the statistical technique of structural analogy (sensitivity analysis), which helps to comprehend how changes in model inputs impact outputs (Kleijnen, 2010; Gąska et al., 2017). Thus, it is mandatory to analyzethe sensitivityofthe FEA static geometric deflection simulation of a CMM to quantify the influence of various input parameters. The analysis evaluated the M544 CMM's deflection under different parameter settings. Parameters and baseline deflection are the key parameters to investigate the sensitivity of the simulation (Novák et al., 2023). In this study,material Young's modulus, beam cross-sectional area, and dead weight which isthe weight of the CMM's components acting as a static load were used to analyze the simulation sensitivity. A baseline deflection value was established by running the FEA simulation with the baseline parameter values (Material Young's Modulus (GPa)=193, Max. Beam Cross-Sectional Area (mm^2) =50mmX50mm, and Dead Weight (N)=490.5). The FEA simulation (represented by the calculate_deflection function in the code) was assumed to calculate the maximum deflection of the CMM structure under the given parameters.For the sensitivity analysis, the values of each parameter were changed individually by ±5% from the baseline. Furthermore, relative and absolute change metrics as stated in the (Brauen et al., 2020)wereused to quantify the sensitivity of the CMM's deflection to each parameter. The percentage change in deflection to the baseline deflection was represented by the relative change percentage.

2.2. Experimental Work

Experiments were conducted to verify the proposed goal. The M544 Crysta Plus CMM as depicted in figure 3(a) manufacturer handbook (Mitutoyo, 2017) was consulted to determine the design parameters. The machine was a Crysta-plus M544 CMM model manufactured by MITUTOYO, including a TP2 probe and a 2mm stylus diameter. The machine's Maximum Permissible Error (MPE), and performance of the ball are (3.5+4.5L/1000)µm, and 11.3µm respectively. The machine has 4µm volumetric probing error and a 4µm repeatability. The length standard measurement was based on the reflective linear encoder of the CMM, and a working bed of 500mmx400mm as shown in Figure 3(b). Measurement was conducted at a protected environmental temperature of 20 ± 2^0C as per the ISO 10360-2 standard. The error distribution of the CMM resulting from the moving structure deflection i.e. M544 CMM measurement error was analysed. The flatness of the CMM granite bed was measured at 121 distinct rectangular array sample points. The machine installation error was taken to be minor when the measurement was performed. After applying the least squares approach fitting as per Smith and Forbes (2013) to match the samples to the surface, the flatness error of the bed was assessed. Lastly, a validation comparison was performed between the static M544 CMM simulated moving structural error deformation and the fitted flatness error.

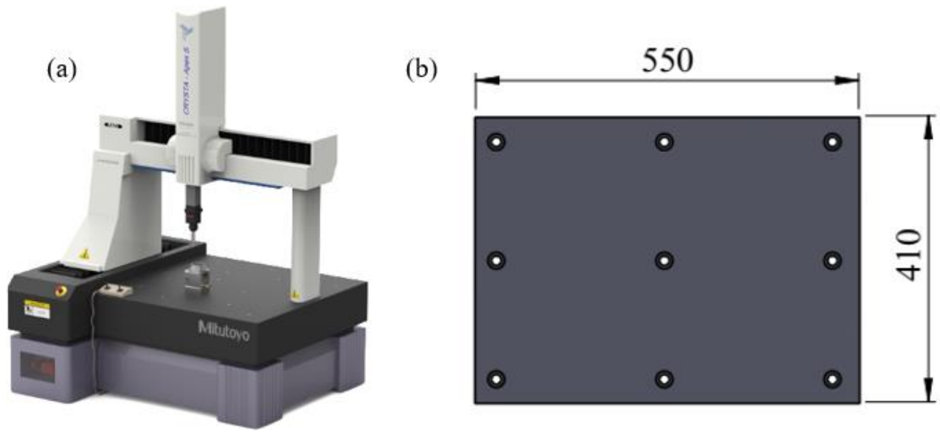


Figure 3. (a) M544 CMM at the University of Osmania Lab (b) A 500 x 400 mm M544 CMM operating bed.

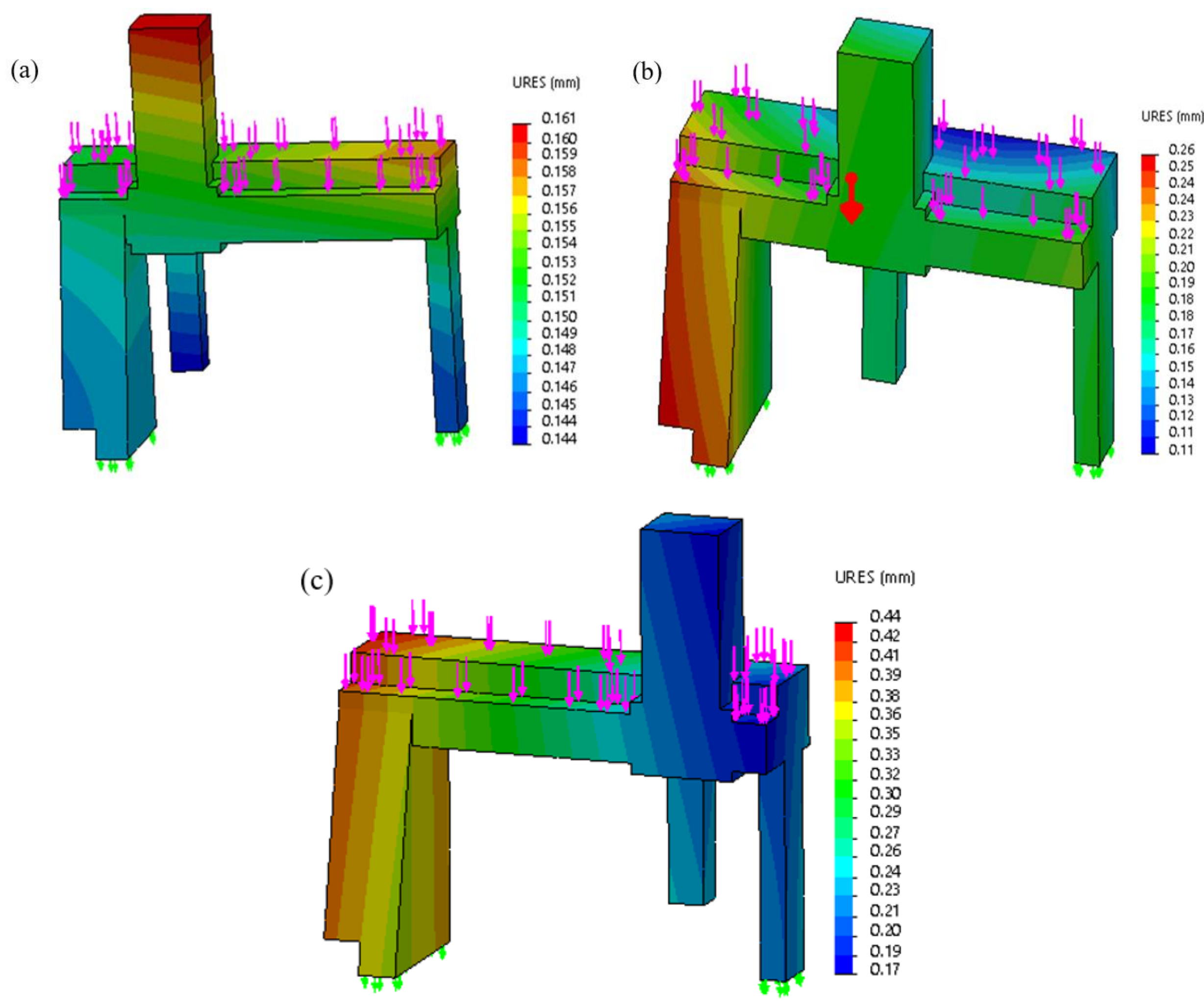


Figure 4. Static finite element analysis of the M544 CMM at three distinct locations: (a) home, (b) center, and (c) right end resultant displacement(URES).

3. RESULT AND DISCUSSION

The right end location of the CMM as shown in figure 4(c) exhibit more deformation of the structure. Unfortunatley, the home site resultant(between the upper and lower defelction) statstic deflection of strucrure found out minimam that is 0.017mm as shown in figure 4(a). The resulatnt defelction at the right end of the M544 CMM location that is 0.27mm, followed by 0.15mm at the middle as shown in figures 4(b) and(c) respectively. This result indicated that higher measurement error proportional to the CMM structure occurred at the right end of the M544 CMM and the lowest is at the home location of the Z-shaft.

On the other hand, the CMM's granite flatbed, 121 sample points were dispersed, and the measurement error was compared. The experimental measurement confirmed that higher measurement flatness error occurred on the right end (500, 0, 0) of the M544 CMM that is 0.466µmm as depicted in figure 5. However, there is contradiction on the home position that the measurement flatness error 0.146µmm is less compared to the middle and right location as shown in figure 5 that is (0, 400, 0).

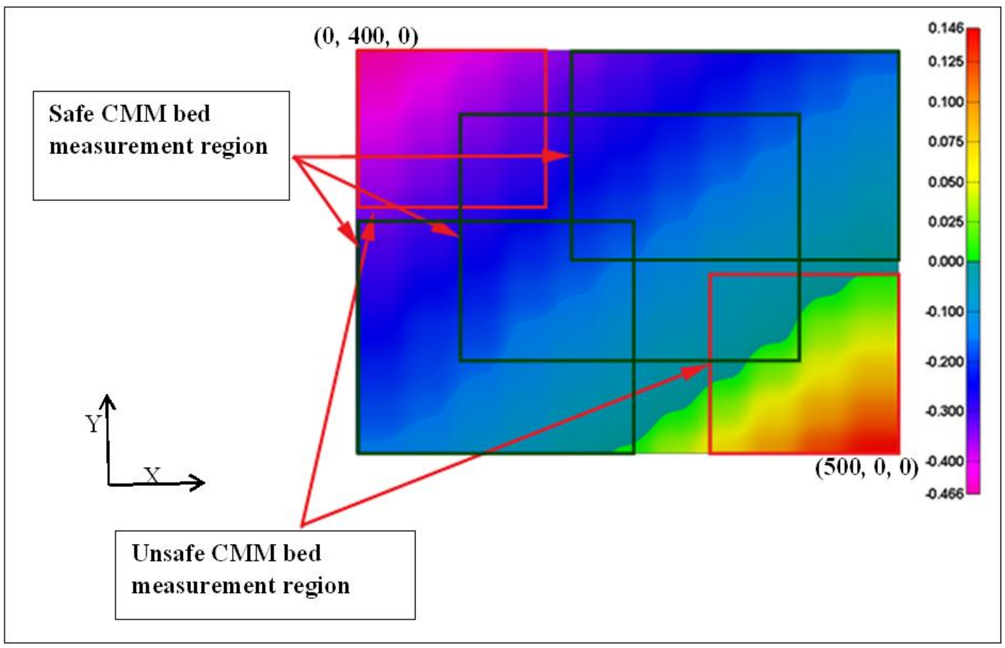


Figure 5. Safe and less safe measurement sites(in micron) on the CMM bed.

A CMM's middle and right corner positions with a higher measurement indicate that the machine's dead weight is influencing, and there is high the static geometric deflection. This phenomenon is caused by the special loading conditions of the moving structure, and result in high bending moment. Similar works by Chan et al. (2021)ABLE686 CMM of MPE of (2.8+L/300) µm was used to obtain flatness error ranges of 0.08 to 1.41 µm, with measurements conducted at room temperature of 20±2°C, which is reasonably in line with this work. This has a detrimental influence on the geometry's form tolerance as verified by Liu et al. (2001). Consequently, the M544 CMM measurement site might be classified as safe or less safe. One has a measurement site with considerable uncertainty and significant static moving structural deformation, whereas the other has a safe site with less deformation. The CMM's right corner locations have more pronounced, less rigid structures. In particular, the corners with coordinates of (500,0,0) exhibit substantial measurement error, as seen in figure 5. The region with the highest measurement errors is indicated by the red box in figure 5.

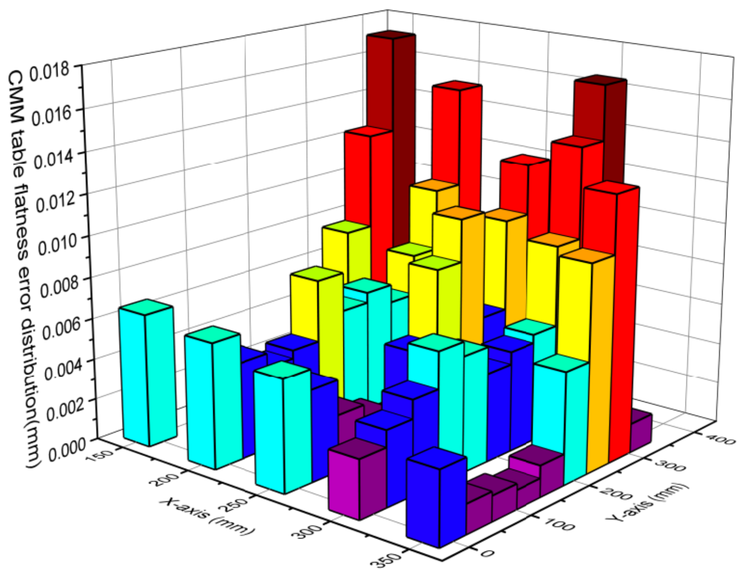


Figure 6. M544 CMM bed flatness error distribution.

Furthermore, figure 6 illustrates the flatness spatial distribution error of the CMM working bed at the ram's constant height of 37.77 mm. The outcome reveals that there is a considerable measurement error at the CMM's far right ends. The most obvious consequence is that measurements made at these sites are not reliable, which result high measurement errors. This led to problems with quality, high rejection, and rework. Consequently, costs of the product rise and output decline. However, to address the result implication further, it is essential to investigate its root cause, implement corrective action, regular calibration, etc. By resolving these problems, it is therefore feasible to enhance the precision and dependability of measurements made using the M544 CMM and lessens the adverse effects of measurement error. In general, it is advised that technical and operators utilize the CMM working granite bed's interior, which is divided into small sections by black boxes, as shown in figure 5 to minimize CMM measurement error.

The resulting deflection change was then calculated by running the FEA simulation with increased and decreased parameter values as shown in table 1. The direct difference in deflection values between the baseline and the deflection obtained with the adjusted parameter value was represented by the absolute change (mm). The relative and absolute changes were tested in both up and down directions for its robustness. Increased and decreased values of the M544 CMM static deflection were also recorded at different parameters. As shown in figure 7, the Material Young's Modulus has the most significant influence on the CMM's deflection, as evidenced by the higher relative change values (>60%) compared to the other parameters followed by dead weight (>20%).

Table 1. Sensitivity analysis results.

Parameter	***Baseline Deflection (mm)***	***Increased Value Deflection (mm)***	***Decreased Value Deflection (mm)***	***Relative Change Up (%)***	***Relative Change Down (%)***	***Absolute Change Up (mm)***	***Absolute Change Down (mm)***
Material Young's Modulus	0.01	0.0095	0.0105	-5.00	5.00	-0.0005	0.0005
Beam Cross-Sectional Area	0.01	0.0099	0.0101	-1.00	1.00	-0.0001	0.0001
Dead Weight	0.01	0.0102	0.0098	2.00	-2.00	0.0002	-0.0002

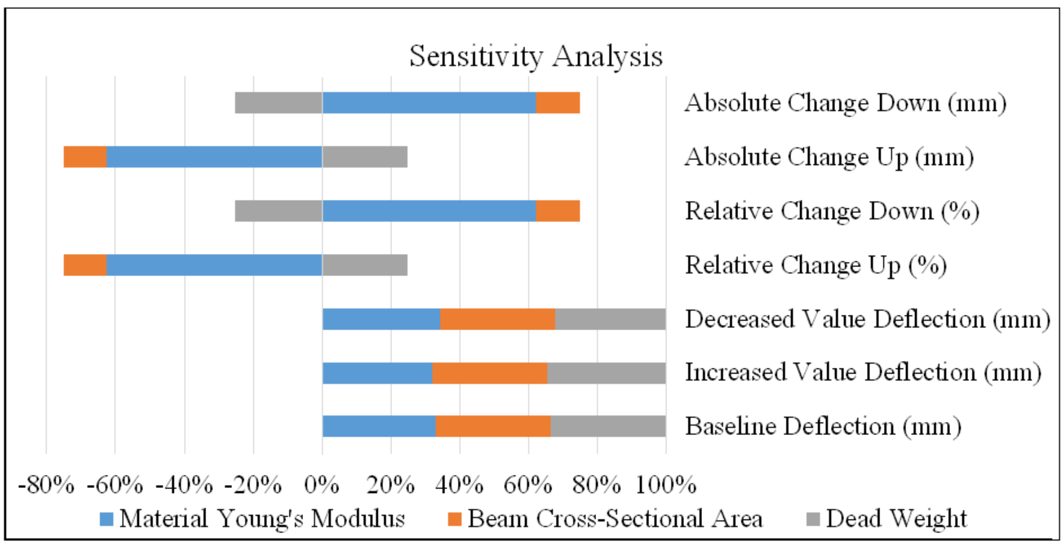


Figure 7. Sensitivity analysis of dominant parameters.

The Beam Cross-Sectional Area exhibits a minimal effect, while the Dead Weight shows a moderate impact on deflection. The sensitivity analysis highlights the importance of considering material properties like Young's Modulus and dead weight during M544 CMM design to minimize static geometric deflection. The analysis also emphasizes the potential benefits of optimizing the CMM's structural design to reduce deflection sensitivity that causes CMM measurement error.

4. CONCLUSIONAND FUTURE RESEARCH DIRECTION

The numerical and experiment results indicate that it is best to use the middle location, which is at least 150mm from the working bed's edge while doing task-specific measurements with the M544 CMM. The experimental measurement verified that the home position, which is 0.146 µmm, and the right end (500, 0, 0) of the M544 CMM, which is 0.466µmm, had larger measurement flatness spatial distribution error. Accurate measurements require compensating for error correction and taking into consideration the static moving structural deflection of the M544 CMM structure while collecting measurements away from the central bed of the device. Measurements made at the extremities of the two ends should be avoided.M544 CMM operators can reduce measurement error caused by M544 CMM reduced structural rigidity by dividing their working table into safe and less safe sections and conducting measurements accordingly. A revised M544 CMM design that considers strengthening the structure in deflection-prone locations may be taken into consideration. Moreover, it is recommended to employ M544 CMM measurement error mitigation measures, including vibration isolation, temperature management, regular calibration, structural reinforcement, and optimum measurement planning. Putting temperature controls in place to manage temperature fluctuations in the CMM environment is a remedy to control thermal error. Interim and routine CMM calibrations, and compensations should be conducted to account for geometric inaccuracies of static geometric displacement M544 CMM. By carefully choosing the measurement site on the CMM working table, users of M544 CMMs could reduce measurement error. An extension of this study and a future effort for the author are case studies that make use of artifacts at various locations on the CMM bed to further confirm the conclusions.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Given that no funding or support is provided by a third party, there is no conflict of interest.

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