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Challenges in Correlating FEA and DIC Measurements: A Case Study on CNC Gantry Design

Abhay Singh[1], Dr. Manu Sharma[2], Dr. Prashant Jindal[3]

[1] *Research Scholar, University Institute of Engineering and Technology, Panjab University, Chandigarh, India*
[2] *Professor, University Institute of Engineering and Technology, Panjab University, Chandigarh, India*
[3] *Associate Professor, University Institute of Engineering and Technology, Panjab University, Chandigarh, India.*

Abstract: Integrating Finite Element Analysis (FEA) and Digital Image Correlation (DIC) has become a standard approach in experimental validation of structural designs. However, discrepancies between FEA predictions and DIC measurements remain challenging, particularly in dynamic systems. This study explores the correlation challenges encountered in a CNC gantry's structural design and vibration analysis. A detailed FEA was performed to predict the structural rigidity characteristics, while experimental validation was conducted using DIC. Significant deviations were observed between numerical and experimental results, highlighting the limitations of FEA modeling assumptions and potential errors in DIC calibration. The study further investigates potential sources of mismatch, including boundary conditions, material properties, etc. The findings emphasize the need for refined simulation techniques and improved experimental setups for better correlation. This research provides valuable insights into the practical limitations of combining FEA and DIC, offering recommendations for enhancing accuracy in future studies.

Keywords: *FEA, DIC, CNC Gantry, Vibration Analysis, Structural Validation, Experimental Correlation*

1. Introduction

Finite Element Analysis (FEA) is widely used for structural analysis, providing predictive insights into stress distribution, deformation, and dynamic behavior. However, its accuracy is often validated against experimental techniques, such as Digital Image Correlation (DIC), which enables non-contact full-field strain measurements. Despite advancements in both methods, discrepancies between FEA predictions and DIC results persist, especially in complex structures like CNC gantries. This study investigates the root causes of these inconsistencies by analyzing the structural response of a CNC gantry through FEA and comparing it with DIC measurements obtained during experimental testing. The objective is to identify sources of error, refine modeling techniques, and improve measurement accuracy. This problem has been highlighted in other structural dynamics case studies; one example involves welding-based experimental mismatches discussed in section 2 [1].

2. Literature Survey

The study on strain-based design in welded structures investigates methodologies for improving the mechanical performance and durability of weldments under cyclic and extreme loading conditions, employing digital image correlation (DIC) and finite element modeling (FEM) to evaluate strain distributions and crack initiation points. The results highlight the significance of residual stresses and microstructural changes in determining fatigue life and structural integrity, providing a basis for optimizing weldment designs in critical engineering applications [1].

Another study integrates finite element model updating (FEMU) techniques with DIC to refine numerical models, capturing full-field displacement and strain data for iterative FEM corrections. Experimental validation demonstrates improved accuracy in predicting deformation behavior, establishing FEMU-DIC as a reliable tool for structural and material analysis [2].

The compliance-based beam method (CBBM) is utilized to determine traction-separation laws (TSLs) in mode I and mode II fracture conditions. It employs DIC to extract displacement fields and assess fracture toughness using R-curves. Key findings include the identification of a compression phase within the cohesive zone and a zero-sliding point near loading areas, contributing to advancements in cohesive zone modeling (CZM) techniques[3]. Another investigation determines traction-separation relationships by applying closed-form integral methods to adhesively bonded double cantilever beam (DCB) and end-notch flexure (ENF) specimens, utilizing DIC to capture displacement distributions and evaluate cohesive zone properties. The results reveal previously overlooked phenomena, such as compressive phases in cohesive zones and zero-sliding points, with extracted TSLs validated through finite element simulations, demonstrating the efficacy of integral-based approaches for fracture mechanics applications [4].

This study addresses fundamental gaps while analyzing a large machine tool structure with FEA and DIC. It lays the groundwork for future work using mixed-mode modeling to improve experimental validation results for monolithically cast structures.

3. Methodology for Gantry Structure Optimization

This chapter outlines the methodological approach to designing, optimizing, and evaluating the CNC machine gantry. The study integrates theoretical analysis, numerical simulations, and material selection to develop an optimized moving gantry structure. The methodology ensures the gantry achieves maximum rigidity, minimal deflection, and enhanced vibration-damping properties.

3.1 Machine for which optimal gantry was designed

The CNC machine (often referred to as CNC router), selected for its widespread use in the market, was chosen due to its popularity and the frequent structural deficiencies in its gantry design. Many machines in the market suffer from poor gantry design, offering significant potential for improvement. The machine features a working area of 8 feet by 4 feet, providing a balance of space and operational flexibility while highlighting areas where dynamic performance and stability can be significantly enhanced.

Figure 1: CNC routers available in the Indian market

3.2 Structural Analysis and Design Modifications

The initial assessment involved identifying weaknesses in the CNC Routers existing in the market, which are mentioned below:

1. Gantry Rigidity: The structural frame exhibited deflections under load, affecting machining precision.
2. Material Properties: The mild steel construction resulted in high stiffness but lacked damping characteristics.
3. Vibration Sensitivity: The rectangular crossbeam design was prone to transverse mode vibrations.
4. Column Strength: The single-plate column mounting reduced overall structural stability.

3.2.1 Design Modifications

(i) Change of the material of construction:

The gantry was redesigned using cast iron instead of mild steel to address these limitations. Casting offered multiple advantages, including:

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1. Improved damping capacity to mitigate vibrations.
2. A monolithic structure that minimized joint-induced weaknesses.
3. Ability to manufacture complex geometric design changes

The casting process required creating a wooden pattern with multiple cores to precisely shape the gantry. The final cast iron gantry was machined using an 8-foot-long shaper machine to mount feed drive components precisely.

(ii) Optimization of rigidity of structure:

The machine gantry was thought of in 3 parts: Two gantry columns and a Cross-beam.

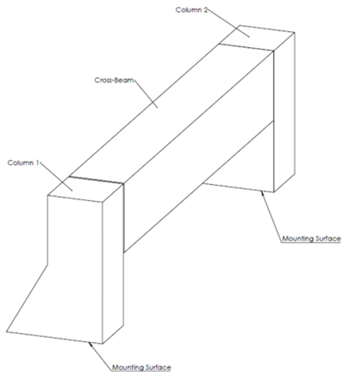

Figure 2: CNC router gantry

The rigidity of the gantry was enhanced through the following steps:

1. The cross-section of the gantry cross-beam was changed from rectangular to square.
2. The wall thickness of the cross-beam was iteratively adjusted to achieve the optimal rigidity.
3. The geometry of the columns was intuitively modified by increasing the mounting surface area and altering the shape to improve rigidity.
4. Special attention was given to the interface between the cross-beam and columns, where stiffeners were strategically added, connecting both columns and the cross-beam.

The overall rigidity of the gantry structure was further improved by refining the geometry and performing Modal analysis using the commercial FEA software ANSYS™. The design was iteratively adjusted and analyzed to determine the optimal configuration, which achieved the highest fundamental natural frequency (Figure 3). Details of the boundary conditions and Modal analysis method are provided in the table below:

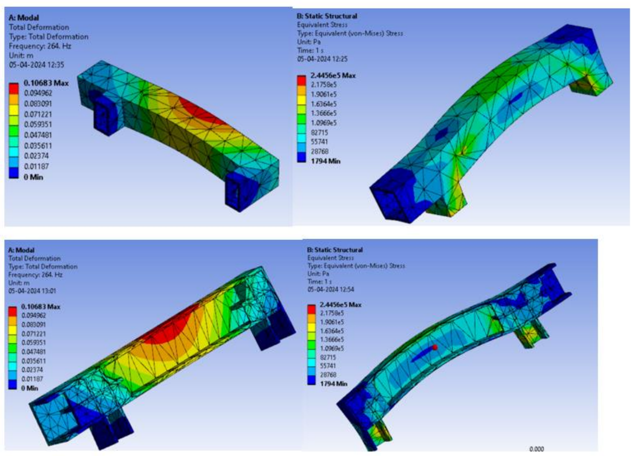

Figure 3: Mode shape of the fundamental natural frequency of the gantry @ 264Hz

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Table 1: (a) Modal analysis method and boundary condyions (ANSYS™)
(b) Modal analysis results

Property	Method/Value
Meshing	Program controlled
Refinement level	3
Boundary condition	Fixed support(column's base face)
Material	Cast iron (FG220 Custom Values)

(a)

Mode	Natural Frequency (Hz)
1	264
2	333.32
3	357.38

(b)

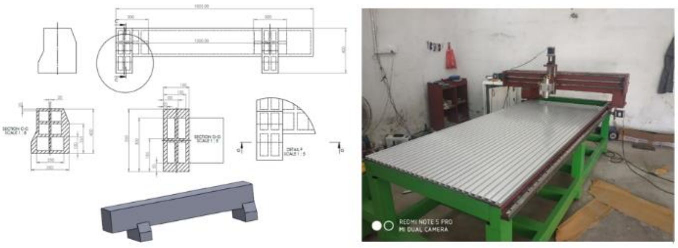

Figure 4: Final optimized gantry design and fabricated machine

4. 4. Experimental Testing and Results

The rigidity of the final machine was tested with Digital Image Correlation (DIC). DIC is done by setting up two cameras focused on the gantry. The surface of the gantry is prepared for the DIC experiment by painting random speckles on the gantry surface painted white (Figure 5). The Vic 2-D (Correlated Solutions) software compares the position of the speckles during excitation to find deformations and natural frequencies during the dynamic conditions induced during the experiment. The details of the experiment are listed in the Table 1. The gantry was excited with the help of impact hammer and the response was captured with help of the cameras.

Table 2: DIC Experiment camera setup and other parameters

S.No.	Equipment/Experimental setup	Value
1	Camera Make	Protron SA5 , Twin Cameras
2	Resolution and Sensor	One mega-pixel, CMOS
3	Lighting	LED floodlight Placed to illuminate speckle pattern
4	Sampling rate	2000 frames/sec
5	Camera Setup	Twin camera, stereoscopic imaging 1220mm away from the gantry
6	Software	Correlated Solutions Vic-2D
7	Calibration Method	Standard
8	Excitation method	Impact hammer

Figure 5: Experimental setup and Speckled Gantry

4.1 Results

The experimental results are presented in two parts: one includes the FFT of the impact response, while the other illustrates the deformations in the Z-direction at three distinct natural frequencies.

4.1.1 FFT of the response

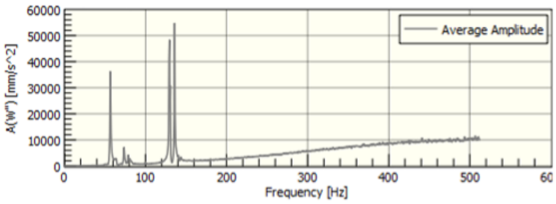

Figure 6: FFT of the Impact Response

We can clearly see the three peaks at 56 Hz, 127 Hz, and 136 Hz. These natural frequencies deviate from the natural frequencies observed in modal analysis. The system's fundamental frequency is greatly reduced, which we will discuss in section 4.

4.1.2 Accelerations captured by DIC cameras

In the DIC experiment, the exact mode shapes at the natural frequencies can be identified, providing a clearer understanding of the system's dynamic behavior at those frequencies. This section presents three images showing the **accelerations** in the dominant Z-direction at specific natural frequencies. Since the span of the actual gantry is very large, the gantry response was assumed to be symmetrical, and the response was calculated on one symmetric half of the gantry.

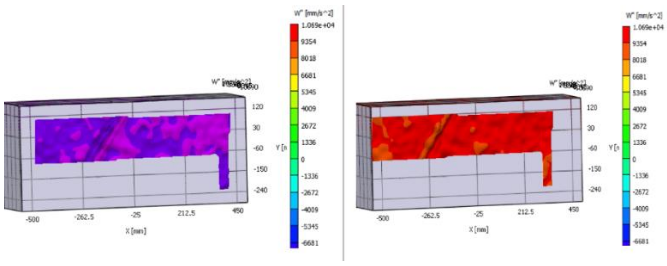

Figure 7: Colour contours of acceleration in impact response $(w\ direction)$ at the second natural frequency

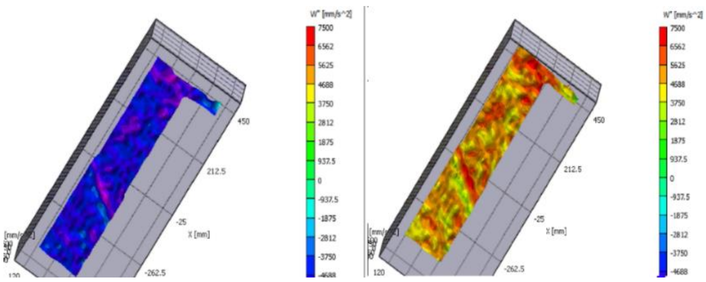

Figure 8: Colour contours of acceleration in impact response $(w\ direction)$ at the second natural frequency

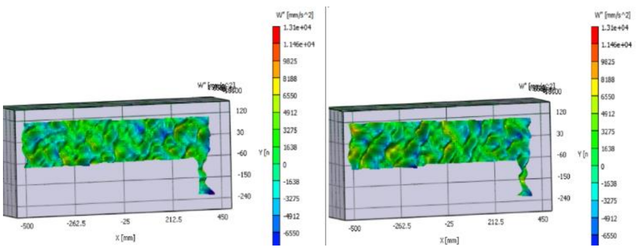

Figure 9: Colour contours of acceleration in impact response $(w\ direction)$ at the third natural frequency

The acceleration pattern of the first mode shape aligns well with the FEA results, but there is a significant variation in frequency. This indicates that the methodology is valid, though certain factors have contributed to a reduction in the actual fundamental frequency compared to the FEA predictions. These factors present crucial challenges when measuring the response of large objects using DIC cameras, which will be discussed in detail in the next section.

5. Discussion

This study's discrepancies between FEA and DIC results are primarily attributed to deviations in material properties, manufacturing tolerances, and experimental boundary conditions. Additionally, the DIC cameras' spatial resolution and calibration accuracy have significantly influenced the deformation measurements. The specific factors contributing to these differences are listed below and discussed thereafter.

1. Imperfect boundary conditions:

Fixed support boundary conditions on the base of the columns may not be justified as the mounting plate acts as a cantilever. The fixed boundary condition may only be applied when the complete base is rested on the base, which should have a minimum stiffness value of 10^7 N/m.

2. Surface defect in casting:

When we observe the deformation plots in Figures 7 and 8, we can see a crease that is not apparent in the original casting. This surface defect is amplified in the DIC analysis results; such defects can also contribute to the mismatch.

3. Insufficient rigidity of feed drive:

The feed drive mechanism, which consists of a linear guide and linear block, may not be rigid enough to be treated as rigid support between the mounting of the column and the column base. This problem is similar to point 1 and will invalidate the assumption of fixed support even after a sufficiently rigid base.

4. Incorrect assumption of symmetry:

Due to the size of the gantry, the response was assumed to be symmetric concerning the center line of the whole gantry. This factor may also contribute to the mismatch

5. Inaccurate definition of bonded surface in ANSYS™:

The stiffeners used to strengthen the gantry were defined as different bodies and were modeled as bonded surfaces attached to the cross-beam and column walls. These stiffeners should be considered single-body with the rest of the gantry geometry, or the definition of the bonded surface should be customized with appropriate parameters.

6. Conclusion

This study investigated the challenges in correlating Finite Element Analysis (FEA) and Digital Image Correlation (DIC) for structural validation of a CNC gantry. The discrepancies observed between the numerical and experimental results highlighted the limitations of both methodologies, including modeling assumptions, boundary conditions, material property estimation, and DIC measurement accuracy.

Through structural modifications and iterative simulations, improvements in model accuracy were achieved, demonstrating the necessity of refined computational approaches and enhanced experimental setups. Adopting cast iron as the primary material significantly improved vibration damping and rigidity, addressing key structural deficiencies identified in the initial analysis.

Despite these advancements, achieving a perfect correlation between FEA and DIC remains complex due to strain localization, camera resolution, and external influences like ambient vibrations. The findings emphasize the need for further research in hybrid modeling techniques, refined DIC calibration methods, and advanced material characterization to enhance predictive accuracy.

Future work should focus on integrating machine learning-based correction factors for FEA-DIC correlation, exploring non-linear material models, and implementing real-time adaptive calibration in experimental setups. These improvements can bridge the gap between theoretical predictions and real-world structural behavior, ensuring more reliable and precise engineering analyses.

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