Design analysis and topology optimization of Vertical Machining Center Spindle Head structure

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Milestones

1961
- Started our journey

1962
- Milling machines production started

1970
- Produced & supplied first Special Purpose Machine

1980
- Launched CNC Boring & Milling machines in India

1984
- Started Horizontal Machining Centers

1986
- Silver Jubilee Year. Exported Machining Centers to USSR

2003
- Introduced Crankshaft Pin Milling machine

2008
- Launched Vertical Turning Centers

2011
- Golden Jubilee Year

2012
- Introduced Front Axle Beam

2013
- Entered into Horizontal Turning business

2016
- Inaugurated Govt. Of India approved Dr. Kalam Center of Innovation

2017
- Launched IRIS

2018
- Inaugurated Hosur Manufacturing Facility
Introduction

• To meet the high precision and efficient development trends of modern CNC machine tool
  – Achieve structural lightweight design
  – Should have high dynamic performance

• Here, structural design of the CNC machine tool Spindle head is a multi-objective optimization issue
Objectives

- To obtain VMC dynamic characteristics using Tool tip FRF and Experimental Modal analysis (EMA)
- Validate FEA model of original Spindle head using EMA data
- To build light weight design of Spindle head by Topology Optimization
- Analyze optimized Spindle head for Static and Dynamic Characteristics
Phase 1: Machine tool **Dynamic Analysis**

- Measuring Tool Tip FRF
- Experimental Modal analysis

**Fig. 1 Tool Tip FRF**

**Fig 2. Modal analysis**
VMC Modal Analysis

Fig.3. Mode shape for 140 Hz

Fig.4. Tool Tip FRF

140 Hz
Phase 2: Numerical Analysis for Spindle head Using COMSOL Multiphysics

- Static analysis
- Dynamic analysis
  - Eigen Frequency analysis
  - Harmonic Response analysis
Structure simplification for FEA

Fig.5. CNC VMC Assembly
Fig.6. Spindle head Assembly
Fig.7. Spindle Head
**Spindle head Loads and Boundary conditions**

**Fig.8. Loads and Boundary Conditions**

<table>
<thead>
<tr>
<th>Loads - Boundary condition and Material</th>
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<tbody>
<tr>
<td><strong>Loads</strong></td>
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<td><strong>Dead weights</strong></td>
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<td><strong>Constraints</strong></td>
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<tr>
<td><strong>Material</strong></td>
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Spindle head Static analysis

Fig.9. Total Displacement
Spindle head **Frequency analysis**

Fig.10. Mode shape (153 Hz)

<table>
<thead>
<tr>
<th>Frequencies (Hz)</th>
<th>Mode shape</th>
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<tbody>
<tr>
<td>153</td>
<td>Bending</td>
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</tbody>
</table>
Spindle head Frequency response analysis
Spindle head FEA Validation

Fig. 13. Mode shape for 140 Hz

Fig. 14. Mode shape for 153 Hz

There is a 9% deviation in numerical analysis data to experimental data.
Spindle head Design Analysis

Fig. 15. Original Spindle head

Fig. 16. Primary design for Spindle head

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Weight (kg)</th>
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<tbody>
<tr>
<td>Original Spindle head</td>
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<tr>
<td>Primary Spindle head</td>
<td>172</td>
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Spindle head Topology Optimization

Fig. 17. Optimized Spindle head

Fig. 18. Total Displacement

Purpose: To improve the static stiffness
Objective: Minimization of structure mass by 15%
Constraints: Static displacement of spindle head need to be < 5 micron
Spindle head Topology Optimization

Fig.19. Original Spindle head

Fig.20. Optimized Spindle head

<table>
<thead>
<tr>
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<td>Original Spindle head</td>
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<td>Primary Spindle head</td>
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Optimized Spindle head Static analysis

Fig. 21. Total Displacement
Optimized Spindle head Frequency analysis

Fig. 22. Mode shape for frequency 173.26 Hz

<table>
<thead>
<tr>
<th>Frequencies (Hz)</th>
<th>Mode shape</th>
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<tr>
<td>173.26</td>
<td>Bending</td>
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Spindle head Frequency response analysis

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)

![Graph 4](image4)
## Results and Discussion

<table>
<thead>
<tr>
<th>Parameters</th>
<th>W/P Material</th>
<th>Original Spindle head</th>
<th>Optimized Spindle head</th>
<th>Improvement(%)</th>
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<td><strong>Topology Optimization</strong></td>
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<td>Mass of structure (kg)</td>
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<td><strong>Static analysis</strong></td>
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<td>Static Displacement (µm)</td>
<td>Aluminium</td>
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<td>5</td>
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<td></td>
<td>Hardened Steel</td>
<td>12</td>
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<td>34</td>
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<td><strong>Frequency response analysis</strong></td>
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<tr>
<td>Frequencies (Hz)</td>
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<td>Aluminium</td>
<td>330</td>
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<td>Hardened Steel</td>
<td>930</td>
<td>420</td>
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Conclusion

- The Experimental Modal Analysis and Tool Tip FRF of the machine, helps to determine the weak stiffness and redundant mass.
- Dynamic and Static stiffness increased 50 & 35 % respectively, by reducing mass with the help of Topology Optimization by 12%.
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