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Design Optimization and Finite Element Analysis of a Six-Cylinder Heavy-Duty Crankshaft using Taguchi Method

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***Abstract*— The crankshaft is a critical component of an internal combustion engine that is continuously subjected to bending, torsional, and cyclic loading conditions. The structural integrity and dynamic performance of the crankshaft directly influence engine reliability, durability, and operational efficiency. In the present study, a six-cylinder heavy-duty crankshaft was modelled using Autodesk Inventor and analysed using ANSYS Workbench. Static structural and modal analyses were performed to evaluate equivalent stress, total deformation, elastic strain, safety factor, and vibration characteristics under operating conditions. A comparative assessment was carried out using Mild Steel (MS), EN19, EN24, and Titanium Alloy materials. Furthermore, Taguchi optimization was employed to identify the optimal geometric parameters for minimizing stress concentration and improving structural performance. The results indicate that EN19 and EN24 exhibit superior stiffness, lower deformation, and improved vibration resistance compared to the other selected materials. The Taguchi optimization analysis identified the optimal combination of crankpin diameter, main journal diameter, and fillet radius, resulting in enhanced structural reliability and load-bearing capability. The proposed methodology provides an effective approach for the design and optimization of heavy-duty crankshafts used in modern engine applications.**

***Index Terms*— Crankshaft, Finite Element Analysis, Modal Analysis, Taguchi Method, Structural Optimization, Heavy-Duty Engine.**

I. INTRODUCTION

The crankshaft is one of the most critical rotating components in an internal combustion engine and is responsible for converting the reciprocating motion of the piston into rotary motion. During engine operation, the crankshaft is continuously subjected to complex loading conditions, including bending, torsional, and cyclic stresses. These loading conditions can lead to excessive deformation, vibration, fatigue failure, and reduced service life if the crankshaft is not properly designed and optimized.

The increasing demand for high-performance and heavy-duty engines has created a need for crankshafts with improved strength, stiffness, durability, and vibration resistance. Material selection and geometric optimization play a significant role in enhancing crankshaft performance while maintaining structural reliability under severe operating conditions.

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Modern design approaches utilize Computer-Aided Design (CAD) and Finite Element Analysis (FEA) techniques to predict stress distribution, deformation behaviour, and dynamic characteristics before manufacturing.

Finite Element Analysis has become a widely accepted tool for evaluating the structural integrity of engine components due to its ability to simulate realistic loading conditions and identify critical stress concentration regions. In addition, modal analysis is commonly employed to determine the natural frequencies and vibration characteristics of mechanical components to avoid resonance-related failures during operation.[1], [3], [9], [15].

II. LITERATURE REVIEW

Several researchers have investigated the structural behaviour and optimization of crankshafts using finite element analysis and advanced design techniques. Their studies have contributed significantly to improving crankshaft strength, fatigue life, and dynamic performance.

Deshbhratar and Suple [1] carried out finite element analysis of an internal combustion engine crankshaft and reported that critical stress concentrations occur near the fillet regions. Their study demonstrated the effectiveness of FEA in identifying failure-prone locations and improving crankshaft reliability.

Fonte et al. [2] investigated the fatigue behaviour of crankshafts subjected to cyclic loading conditions. The results indicated that fatigue failure is strongly influenced by stress concentration and material properties, emphasizing the importance of proper design and material selection.

Yu and Tian [3] performed structural optimization of crankshaft geometry using numerical simulation techniques. Their findings showed that increasing crankpin dimensions and optimizing fillet geometry significantly reduced stress concentration while improving structural stiffness.

Nazha and El-Sayed [4] conducted a comparative study on different crankshaft materials and reported that high-strength alloy steels provide improved load-bearing capacity, lower deformation, and enhanced fatigue resistance when compared with conventional materials.

Recent studies have also highlighted the effectiveness of Taguchi optimization techniques in reducing the number of simulation trials while achieving reliable design improvements. The integration of finite element analysis with statistical optimization methods has proven to be an efficient approach for enhancing crankshaft performance and durability under severe operating conditions [5].

Based on the literature review, it is evident that both material selection and geometric optimization play a crucial role in improving crankshaft structural integrity and vibration characteristics. Therefore, the present study focuses on the static structural analysis, modal analysis, material comparison, and Taguchi-based optimization of a six-cylinder heavy-duty crankshaft.

III. METHODOLOGY

A. CAD Modelling

A three-dimensional model of the six-cylinder heavy-duty crankshaft was developed using Autodesk Inventor based on standard crankshaft design dimensions and geometric specifications. The CAD model included all major features such as crankpins, main journals, crank webs, fillet regions, and oil holes. Special attention was given to maintaining dimensional accuracy and geometric continuity to ensure realistic simulation results during finite element analysis.

The developed CAD model served as the basis for static structural and modal analyses performed in ANSYS Workbench. The model was subsequently exported in a compatible format and imported into the analysis environment for meshing, boundary condition application, and numerical simulation. The accurate representation of crankshaft geometry enabled effective evaluation of stress distribution, deformation characteristics, and vibration behaviour under operating conditions.

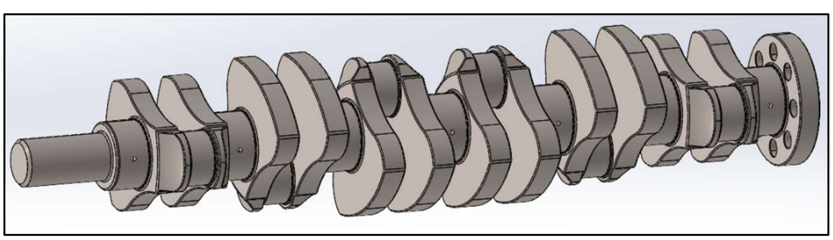

Figure 1. 3D CAD Model of the Six-Cylinder Heavy-Duty Crankshaft

B. Material Selection

The mechanical performance of a crankshaft is significantly influenced by the material used in its construction. To evaluate the effect of material properties on structural and dynamic behaviour, four different materials were selected for analysis: Mild Steel (MS), EN19, EN24, and Titanium Alloy. These materials are commonly used in automotive and heavy-duty engine applications due to their favourable strength, stiffness, and fatigue characteristics.

Mild Steel was considered as a conventional engineering material, while EN19 and EN24 were selected because of their high strength and excellent load-bearing capability. Titanium Alloy was included due to its high strength-to-weight ratio and corrosion resistance. The material properties used in the finite element analysis are presented in Table I.

TABLE I. MATERIAL PROPERTIES USED FOR ANALYSIS

Material	Young's Modulus (GPa)	Density (kg/m³)	Poisson's Ratio	Yield Strength (MPa)
Mild Steel (MS)	200	7850	0.3	250
EN19	210	7850	0.29	415
EN24	210	7850	0.3	680
Titanium Alloy	110	4430	0.34	880

The selected materials represent a wide range of mechanical properties, enabling a comprehensive comparison of stress distribution, deformation behaviour, elastic strain, and vibration characteristics. The comparative evaluation helps identify the most suitable material for heavy-duty crankshaft applications.

C. Static Structural Analysis

Static structural analysis was performed in ANSYS Workbench to evaluate the stress, deformation, and strain behaviour of the six-cylinder heavy-duty crankshaft under operating conditions. Appropriate meshing, loading, and boundary conditions were applied to assess the structural integrity and load-bearing capability of the selected materials.

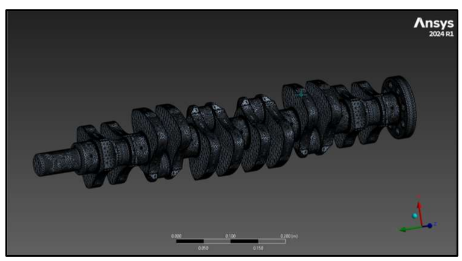

Figure 2. Finite Element Meshing of the EN24 Crankshaft

D. Modal Analysis

Modal analysis was performed to investigate the dynamic behaviour of the six-cylinder heavy-duty crankshaft and determine its natural frequencies and mode shapes. The analysis was conducted using ANSYS Workbench under free vibration conditions. The primary objective of the modal analysis was to evaluate the vibration characteristics of the crankshaft and identify potential resonance conditions during engine operation. The obtained natural frequencies and mode shapes provide valuable information regarding the dynamic stability and vibration resistance of the selected crankshaft materials.

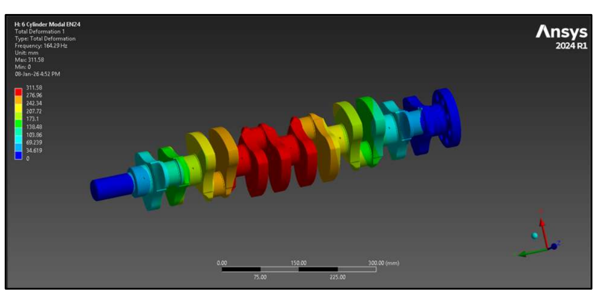

Figure 3. Total Deformation for Mode Shape 1 of the EN24 Crankshaft

TABLE II. NATURAL FREQUENCIES OF DIFFERENT CRANKSHAFT MATERIALS

Mode Shape	MS (Hz)	EN24 (Hz)	EN19 (Hz)	Titanium Alloy (Hz)
1	162.34	164.29	166.28	160.4
2	176.22	178.35	180.51	174.29
3	397.55	402.19	407.07	393.3

E. Taguchi Optimization

The Taguchi optimization technique was employed to identify the optimal geometric parameters for improving crankshaft structural performance and minimizing stress concentration. Three design parameters, namely crankpin diameter, main journal diameter, and fillet radius, were selected as control factors. Each parameter was considered at three different levels, and an L9 orthogonal array was used to reduce the number of simulation trials while maintaining optimization accuracy.

Finite element analysis was performed for each experimental combination defined by the Taguchi L9 orthogonal array. The equivalent stress obtained from each simulation was considered as the response parameter. Signal-to-noise (S/N) ratio analysis was then conducted to evaluate the influence of each design parameter and determine the optimal parameter combination for minimizing stress values and improving crankshaft structural reliability.

TABLE III. TAGUCHI L9 ORTHOGONAL ARRAY FOR CRANKSHAFT OPTIMIZATION

↓	C1	C2	C3	C4
	Crankpin Diameter	Main Journal Diameter	Fillet Radius	Equivalent Stress
1	20	24	0.1	960.42
2	20	27	0.2	945.18
3	20	30	0.3	932.64
4	22	24	0.2	938.75
5	22	27	0.3	920.53
6	22	30	0.1	929.81
7	24	24	0.3	915.22
8	24	27	0.1	924.67
9	24	30	0.2	906.35

The finite element analysis results obtained from each Taguchi experimental run were used to evaluate the influence of design parameters on crankshaft performance. The optimization results and corresponding signal-to-noise ratio analysis are presented and discussed in the Results and Discussion section.

IV. RESULTS AND DISCUSSION

A. Static Structural Results

Static structural analysis was performed to evaluate the mechanical behaviour of the six-cylinder heavy-duty crankshaft under the applied loading conditions. The analysis focused on determining the equivalent stress, total deformation, and equivalent elastic strain developed within the crankshaft. EN24 material was considered as the reference material for detailed result visualization due to its widespread application in heavy-duty crankshaft manufacturing. The obtained results provide valuable information regarding the structural integrity, stiffness, and load-bearing capability of the crankshaft under operating conditions.

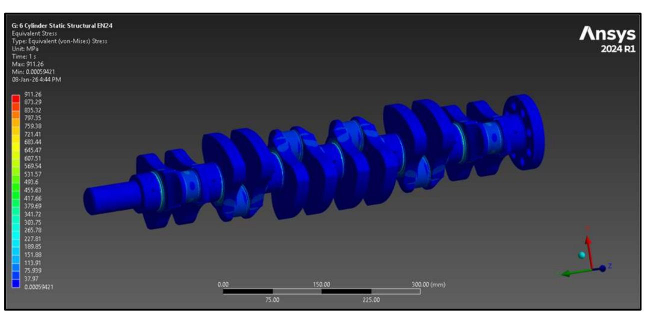

Figure 4. Equivalent Stress Distribution of the EN24 Crankshaft

The equivalent stress distribution obtained from the static structural analysis indicates that the maximum stress occurs near the fillet and crankpin regions, where stress concentration is generally expected. The EN24 crankshaft exhibited a maximum equivalent stress of approximately 911.26 MPa under the applied loading conditions. The stress distribution pattern confirms the ability of the material to withstand operational loads while maintaining structural integrity.

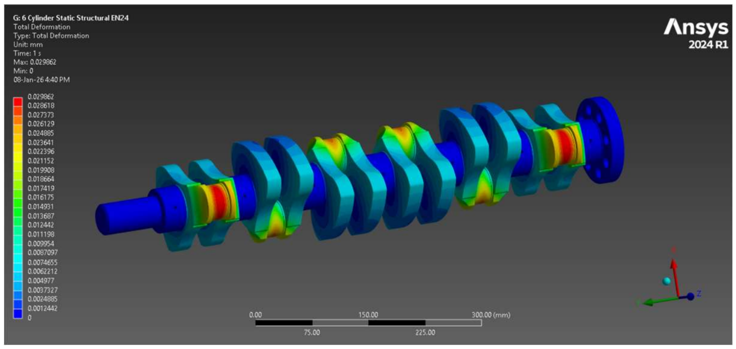

Figure 5. Total Deformation of the EN24 Crankshaft

The total deformation result represents the displacement behaviour of the crankshaft under loading conditions. The maximum deformation obtained for the EN24 crankshaft was approximately 0.029862 mm. The relatively low deformation value indicates high stiffness and adequate resistance to bending effects during engine operation.

B. Material Comparison

TABLE IV. COMPARISON OF STATIC STRUCTURAL ANALYSIS RESULTS

Material	Equivalent Stress (MPa)	Total Deformation (mm)	Elastic Strain
MS	906.35	0.030705	0.004986
EN19	911.26	0.029151	0.004775
EN24	911.26	0.029862	0.004892
Titanium Alloy	884.92	0.056905	0.008847

The comparative analysis indicates that EN19 and EN24 exhibited lower deformation and elastic strain values than Mild Steel and Titanium Alloy, demonstrating superior stiffness and structural rigidity. Although Titanium Alloy showed lower stress values, its higher deformation reduced its suitability for heavy-duty crankshaft applications. EN19 provided the best overall structural performance among the selected materials.

C. Taguchi Optimization Results

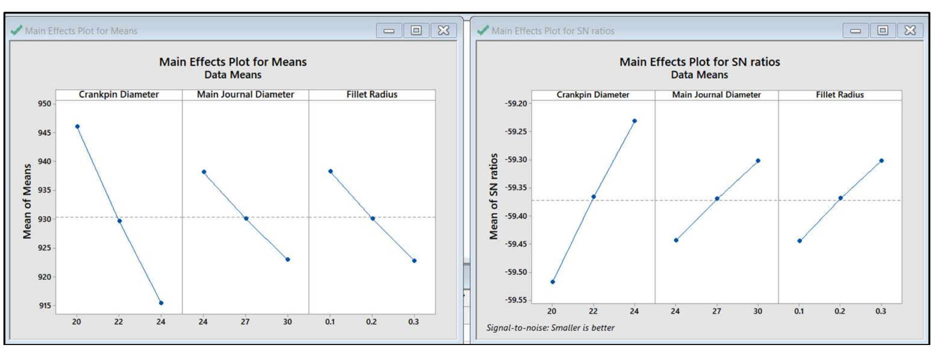

Figure 6. Main Effects Plot and S/N Ratio Plot for Taguchi Optimization

The Taguchi optimization results were evaluated using signal-to-noise (S/N) ratio analysis. The main effects plot indicates the influence of crankpin diameter, main journal diameter, and fillet radius on equivalent stress. Among the selected parameters, fillet radius exhibited a significant effect on stress reduction due to its influence on stress concentration at critical locations. The optimal parameter combination obtained from the analysis was found to improve stress distribution and enhance the structural performance of the crankshaft. The optimization approach effectively reduced the number of simulation trials while identifying the most suitable design configuration.

V. CONCLUSION

In the present study, a six-cylinder heavy-duty crankshaft was modelled using Autodesk Inventor and analysed using ANSYS Workbench to evaluate its structural and dynamic performance. Static structural analysis was performed to determine the equivalent stress, total deformation, and elastic strain, while modal analysis was conducted to investigate the vibration characteristics of the crankshaft. A comparative assessment was carried out using Mild Steel, EN19, EN24, and Titanium Alloy materials. The results indicated that EN19 and EN24 exhibited superior performance compared to the other selected materials due to their lower deformation, reduced elastic strain, and improved vibration resistance. Among all the materials considered, EN19 demonstrated the best overall performance by exhibiting the lowest deformation and elastic strain values along with the highest natural frequencies, indicating excellent stiffness and structural stability. Furthermore, Taguchi optimization successfully identified the optimal design parameter combination for improving stress distribution and enhancing crankshaft reliability. The study confirms that the integration of finite element analysis and Taguchi optimization provides an effective methodology for the design and development of high-performance heavy-duty crankshafts.

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