

Application of CAE Processes

Structural and Fluid Analysis [ACMA6010]

Tyler Powell [2318809]

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1. Introduction

Computer Aided Engineering (CAE) tools are widely used in engineering design to evaluate structural, thermal, and dynamic behaviour prior to manufacture. While CAE can reduce development time and reliance on physical prototyping, its accuracy depends strongly on modelling assumptions, simplifications, and numerical methods.

This report applies CAE techniques to the analysis and iterative improvement of a CPU fan and heatsink assembly, a system subject to both mechanical loading from rotation and thermal loading from heat generation. A kinematic analysis is used to extract operational loads, followed by a thermal analysis of the fan head using convection boundary conditions. These loads are then imported into a static structural analysis to assess the component's structural response.

Design modifications are introduced based on the structural results, and the analyses are repeated to evaluate performance improvements. Validation studies, including mesh sensitivity and simplified analytical comparisons, are used to assess result reliability, while the limitations of CAE tools and modelling choices are critically discussed.

2. Definition and Design Requirements

2.1. System Context and Objectives

The system analysed in this study is an actively cooled CPU fan and heatsink assembly intended for desktop computing applications. The system operates under combined mechanical loading due to fan rotation and thermal loading resulting from elevated operating temperatures within the computer enclosure.

The primary objective of this work is to demonstrate the application of CAE tools to assess the structural and thermal behaviour of a real-world engineering component under representative operating conditions. A further objective is to use the results of these analyses to inform a targeted design modification and to evaluate whether the updated design exhibits improved structural performance.

2.2. Design Requirements and Success Criteria

The design requirements for the system are defined to reflect realistic operating conditions and practical constraints:

- The assembly must be compatible with a standard desktop CPU cooling application.
- The fan is required to operate at a rotational speed of up to 3000 RPM.
- The selected component for detailed analysis, the fan head, must remain structurally sound under combined mechanical and thermal loading.
- Maximum stresses within the component should remain below the material yield strength to ensure elastic behaviour.
- Deformations should be sufficiently small to avoid mechanical interference or loss of functionality.
- The component must operate within acceptable temperature limits defined by the applied thermal boundary conditions.

2.3. Modelling Scope, Assumptions and Simplifications

To ensure numerical stability and efficient computation, the model uses simplified geometry with small features such as fastener threads omitted. Airflow is not explicitly modelled; instead, heat transfer is represented using convection boundary conditions with a prescribed ambient temperature. Material properties are assumed to be homogeneous and isotropic.

The kinematic analysis is used solely to extract reaction forces and moments from fan rotation, while thermal and mechanical loads are subsequently mapped onto a static structural analysis of the fan head. These simplifications are appropriate for an early-stage CAE study.

3. CAE in the Engineering Design Process

3.1. CAE Workflow and Data Transfer Between Analysis

In modern engineering practice, CAE is typically applied through an iterative workflow in which multiple analyses are combined to represent realistic operating conditions. In this study, a kinematic analysis is first used to extract reaction forces and moments from fan rotation, while a thermal analysis evaluates temperature distribution using convection boundary conditions. The resulting mechanical and thermal loads are then mapped onto a static structural analysis of the fan head to assess combined loading effects.

3.2. Common Sources of Error and Uncertainty in CAE

CAE results are sensitive to modelling choices, particularly boundary condition definition, contact formulation, and load application. Small changes in constraints or contacts can significantly influence predicted stresses and deformations. Additional uncertainty arises from the use of simplified representations of complex physical phenomena, such as airflow and heat transfer, and from idealised material property definitions.

Numerical discretisation also affects solution accuracy, as mesh density and element quality influence stress prediction, particularly in regions of high stress concentration. These factors mean that CAE results should be interpreted as approximate indicators of behaviour rather than exact predictions.

4. Literature Review

4.1. Structural Analysis Limitations

Finite Element Analysis (FEA) is extensively used to predict stress and deformation in engineering components; however, its accuracy is strongly dependent on modelling assumptions and boundary condition definition. Linear static FEA assumes small deformations, linear elastic material behaviour, and idealised constraints, which limits its ability to represent real systems that may exhibit contact non-linearity, plastic deformation, or complex joint behaviour (Cook et al., 2007).

Several studies highlight that while FEA is effective for identifying stress distributions and critical regions, absolute stress values can vary significantly depending on constraint application and contact modelling (Bathe, 2006).

4.2. Thermal Modelling Limitations

Thermal analyses in CAE frequently rely on simplified representations of convection using assumed heat transfer coefficients, rather than explicitly modelling fluid flow through Computational Fluid Dynamics (CFD). Incropera et al. (2017) note that convection coefficients are highly dependent on flow conditions, geometry, and surface characteristics, making their accurate estimation challenging without experimental data or CFD.

In electronics cooling applications, simplified thermal models have been shown to capture temperature trends and relative performance changes effectively, but discrepancies in absolute temperature prediction are common (Ellison, 2018). Additionally, material properties such as thermal conductivity and elastic modulus are often assumed constant, despite their known dependence on temperature, introducing further uncertainty in thermo-mechanical simulations.

4.3. Contact, Boundary Condition, and Meshing Sensitivity

The sensitivity of CAE results to contact definitions, boundary conditions, and mesh density is well documented in the literature. Incorrect or overly stiff boundary conditions can artificially constrain components, leading to unrealistically low deformation or elevated stress predictions (Cook et al., 2007). Similarly, contact formulations such as bonded or frictionless contacts can significantly alter load transfer paths within assemblies.

Mesh dependency is another critical source of numerical uncertainty. Bathe (2006) emphasises that stress concentrations are particularly sensitive to mesh refinement, and that mesh convergence studies are essential to ensure reliable results. However, increasing mesh density must be balanced against computational cost, especially for complex assemblies.

4.4. Validation Expectations in Published Practice

Validation of CAE models is typically achieved through comparison with analytical solutions, experimental measurements, or established benchmark problems. In practice, published studies often demonstrate validation through convergence trends and qualitative agreement rather than exact numerical matching (Cook et al., 2007). Mesh independence studies and sensitivity analyses are widely regarded as minimum requirements for demonstrating model credibility.

The literature consistently emphasises that CAE results should be interpreted as approximations that support engineering judgement, rather than definitive representations of real-world behaviour (Bathe, 2006).

5. CAD Modelling Development

5.1. Assembly Overview and Component List

The CAD model developed for this study represents an actively cooled CPU fan and heatsink assembly. The assembly was created to reflect a realistic mechanical system while remaining suitable for efficient CAE analysis. The model consists of multiple interacting components that collectively provide structural support, airflow generation, and thermal management.

Component	Quantity
Fan Head	1
Fan shroud	1
Motor Housing	1
Heatsink	1
Base plate	1
Fan shroud fasteners	4
Base plate fasteners	4
Fastener Springs	4

These components were assembled to reflect their functional relationships, with appropriate alignment and positioning to allow kinematic, thermal, and structural analyses to be performed. For detailed analysis, the fan head component was selected as the primary focus due to its exposure to both mechanical loading from rotation and thermal loading from the surrounding environment.

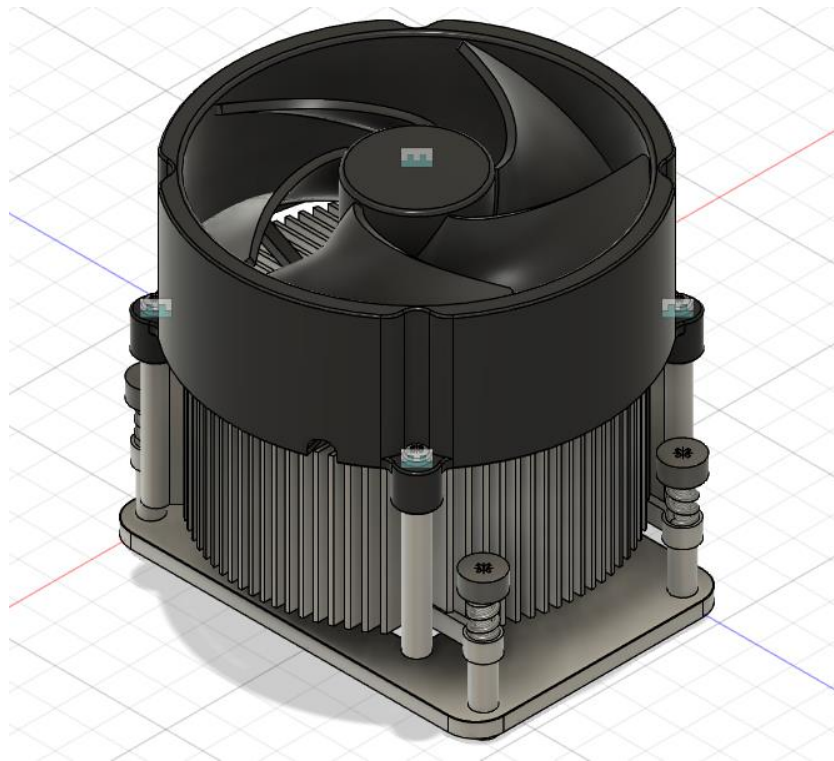


Figure 1: CPU Fan Cooler Heatsink Isometric View

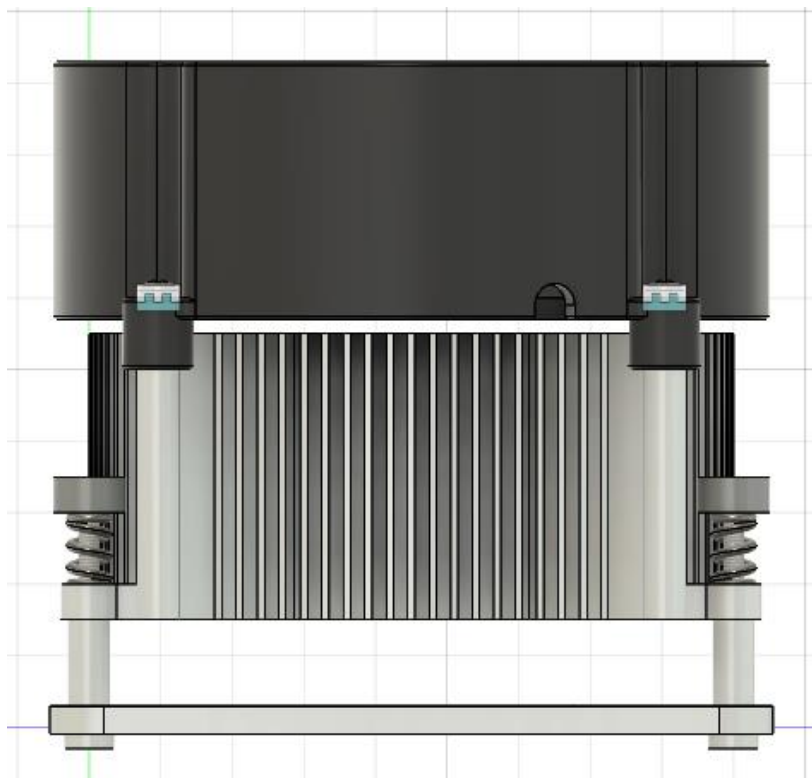


Figure 2: CPU Fan Cooler Heatsink Side View

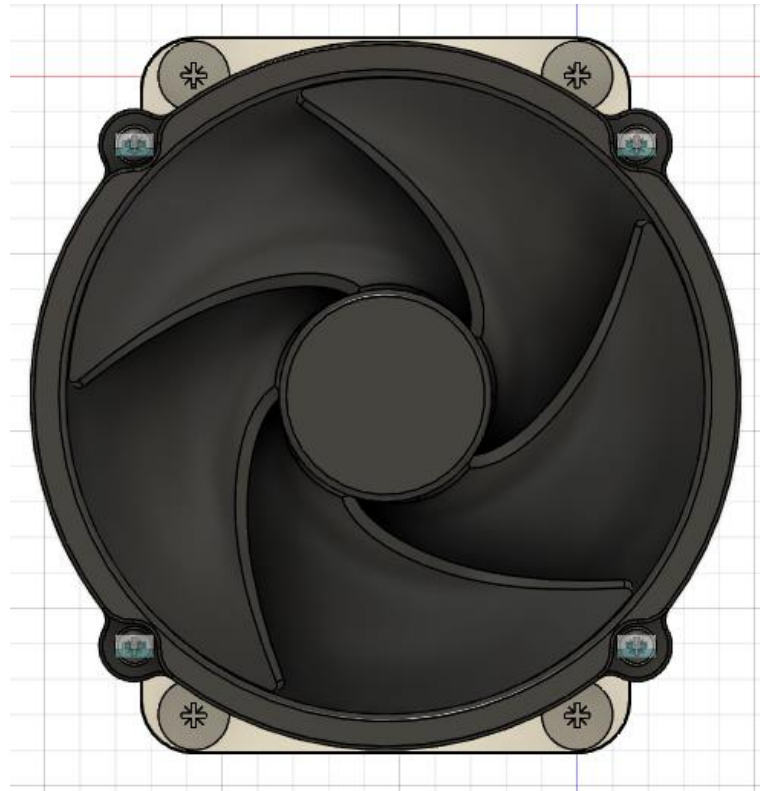


Figure 3: CPU Fan Cooler Heatsink Top View

5.2. Geometry Preparation for CAE

To improve numerical stability and reduce computational cost, the CAD geometry was simplified prior to import into ANSYS. Small features such as fillets, chamfers, and fastener threads were removed, as they have minimal influence on global behaviour but negatively affect mesh quality.

Detailed fasteners and compression springs were initially included but caused meshing and contact convergence issues due to their complex and slender geometry. These components were therefore removed or idealised, with their structural effect represented using simplified bonded contacts and constraints. This approach preserves the primary load paths while avoiding unnecessary numerical complexity.

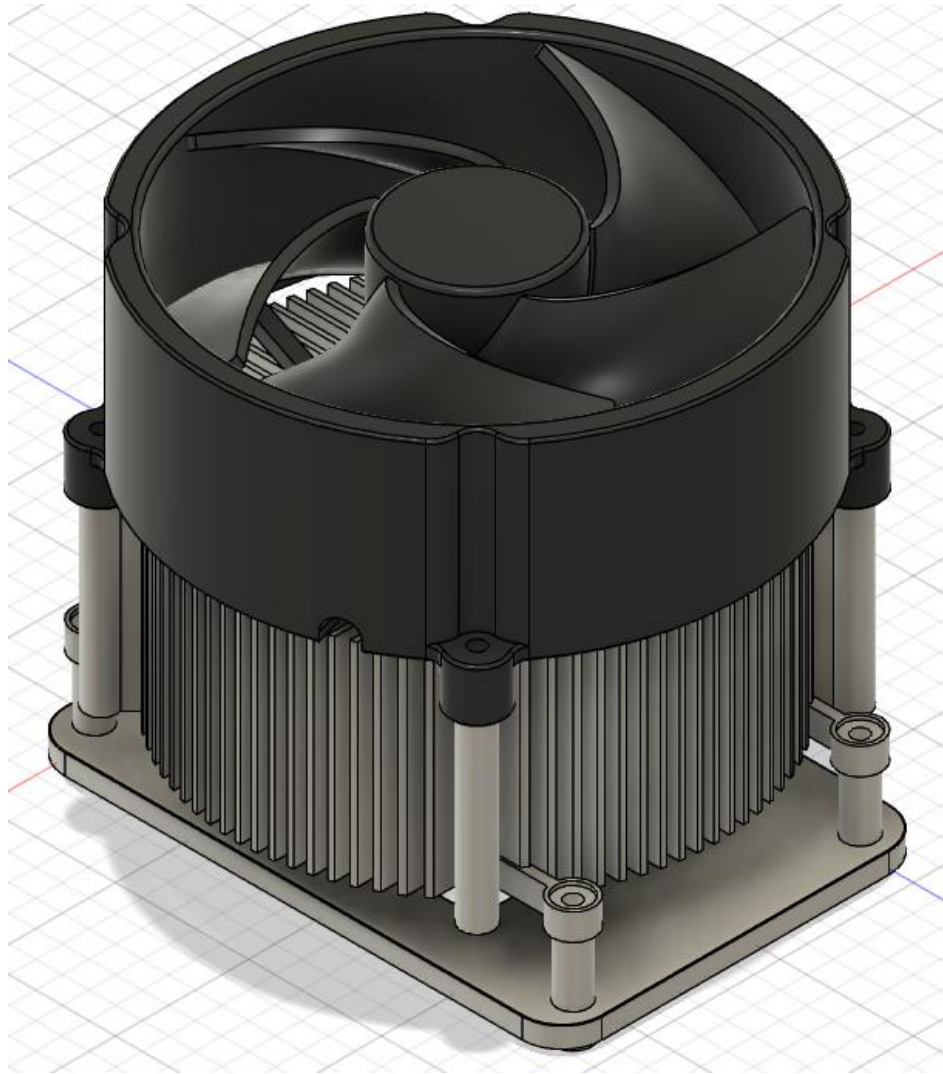


Figure 4: CPU Fan Cooler Heatsink with Removed Fasteners and Springs

5.3. Materials Selection and Property Definition

Material selection for the CAD model was based on typical materials used in consumer electronics cooling applications. Each component was assigned a homogeneous, isotropic material model within ANSYS. The fan head and housing were modelled using a polymer material representative of ABS plastic, while metallic components such as the heatsink and mounting elements were assigned aluminium or steel material definitions as appropriate.

Material properties including Young's modulus, Poisson's ratio, density and thermal conductivity were defined to enable coupled thermal-structural analysis. Where applicable, temperature-dependent properties were included to better represent material behaviour under elevated operating temperatures.

6. Kinematic Analysis Methodology

6.1. Rigid Dynamics Model Set Up

A kinematic analysis was performed using a rigid dynamics approach within ANSYS to represent the rotational behaviour of the fan during operation. The rigid dynamics formulation was selected as the objective of this analysis was not to capture structural deformation, but to determine realistic operational loads generated by fan rotation.

The fan assembly was isolated within the rigid dynamics environment, and gravitational effects were included to represent realistic operating conditions. Material density was retained to ensure that inertial effects were correctly represented, while elastic deformation was intentionally excluded from this stage of the analysis.

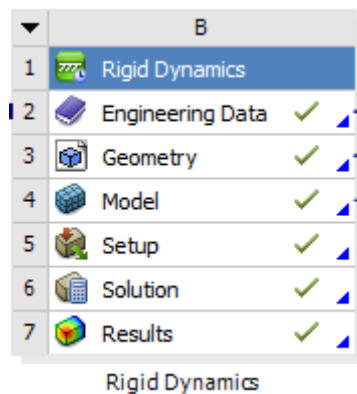


Figure 5: Rigid Dynamics Workbench Set Up

6.2. Joint Definition and Motion Inputs

Fan rotation was defined using a revolute joint between the fan head and the motor housing, with the axis of rotation aligned with the fan's central axis. This joint constrained translational degrees of freedom while allowing rotation about the specified axis, accurately representing the intended mechanical behaviour.

A constant angular velocity corresponding to an operational speed of 3000 RPM was applied to the revolute joint. This value was selected to represent a realistic upper operating condition for a desktop CPU cooling fan. The use of a prescribed rotational speed ensured stable convergence and allowed reaction forces and moments to be extracted consistently from the model.

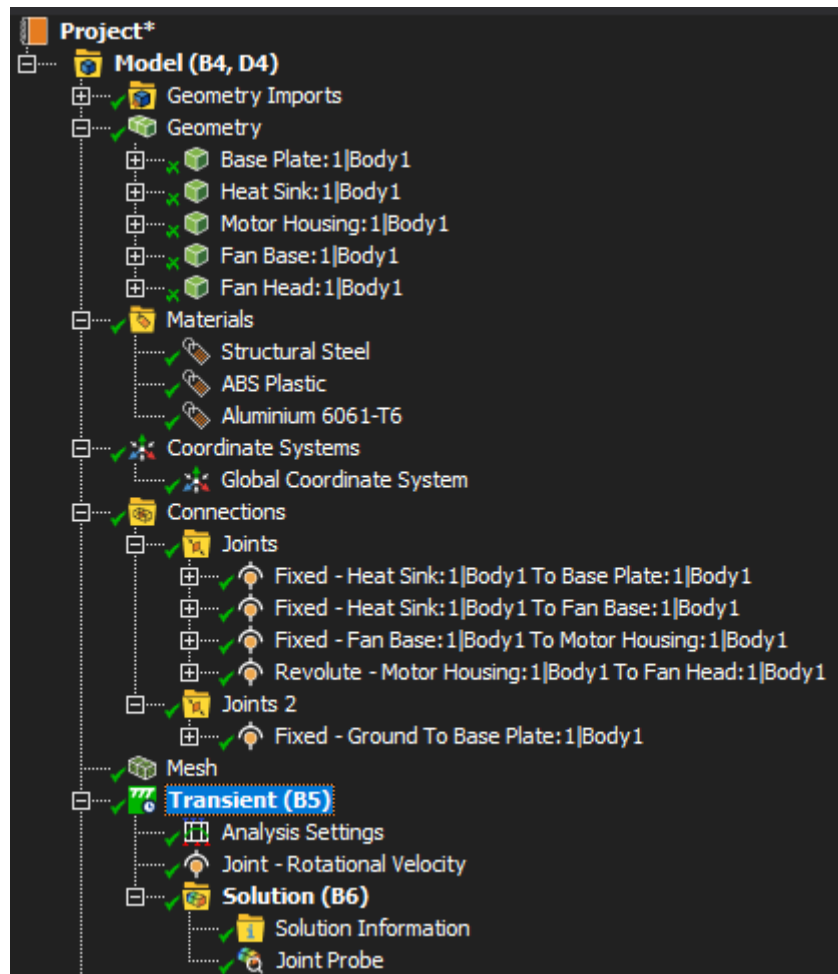


Figure 6: Rigid Dynamics Mechanical Set Up Tree

6.3. Extraction of Operational Loads

The primary outputs of the kinematic analysis were the reaction forces and reaction moments generated at the revolute joint during steady-state rotation. These reaction quantities represent the mechanical loads transmitted through the fan head during operation and form a physically realistic basis for subsequent structural assessment.

The extracted reaction moment was used to define an equivalent torque load, while reaction forces were evaluated to assess their relative magnitude compared to other applied loads. These kinematic results were subsequently imported into the static structural analysis to evaluate the structural response of the fan head under representative operational loading conditions.

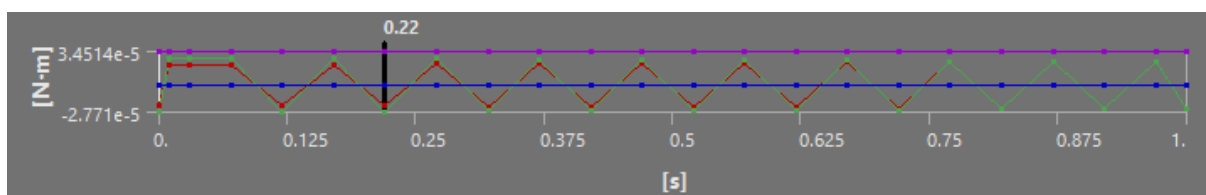


Figure 7: Total Moment from Rotation

Maximum Value Over Time	
☐ X Axis	2.4594e-005 N.m
☐ Y Axis	2.7678e-005 N.m
☐ Z Axis	7.2075e-025 N.m
☐ Total	3.4514e-005 N.m
Minimum Value Over Time	
☐ X Axis	-2.471e-005 N.m
☐ Y Axis	-2.771e-005 N.m
☐ Z Axis	-6.3321e-025 N.m
☐ Total	3.4514e-005 N.m

Figure 8: Min and Max Moment Values

7. Thermal Analysis

7.1. Thermal Model Set Up

A steady-state thermal analysis was conducted to evaluate the temperature distribution within the fan head component under elevated operating conditions. The fan head was analysed in isolation, as it is exposed directly to the surrounding thermal environment and subsequently subjected to combined thermo-mechanical loading in later analysis stages.

Heat transfer to the surrounding air was modelled using convection boundary conditions applied to the exposed surfaces of the fan head. An ambient temperature of 90 °C was prescribed to represent a conservative upper operating condition within a desktop computer enclosure, corresponding to the maximum temperature at which the CPU is expected to operate before thermal throttling. Material thermal properties were defined according to the selected polymer material to enable accurate prediction of temperature gradients within the component.

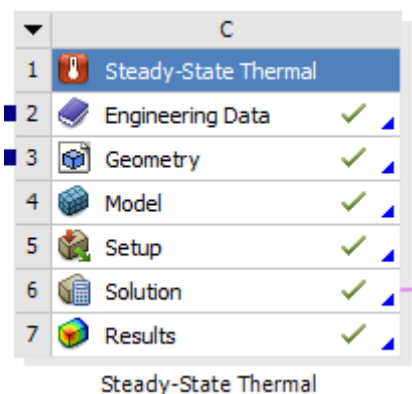


Figure 9: Steady State Thermal Workbench Set Up

7.2. Assumptions and Impact on Accuracy

The thermal analysis employs several simplifications to maintain computational efficiency. Airflow is not explicitly modelled; instead, heat transfer is represented using an assumed convection boundary condition. Radiative heat transfer is neglected, and material properties are assumed to be homogeneous and isotropic.

These assumptions reduce model complexity but introduce uncertainty in absolute temperature prediction. However, they are considered acceptable for generating a representative thermal field suitable for subsequent structural analysis.

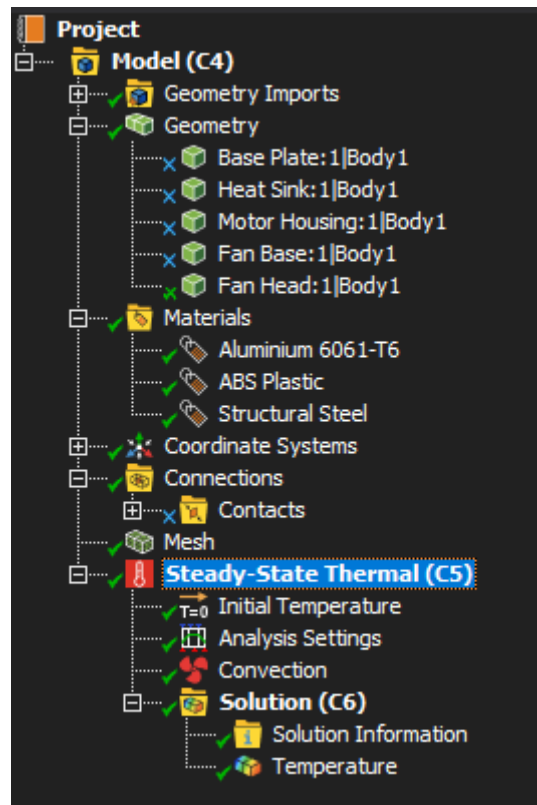


Figure 10: Steady State Thermal Mechanical Set Up Tree

7.3. Extraction of Thermal Conditions

The primary output of the thermal analysis was the steady-state temperature distribution within the fan head. This temperature field was exported and mapped directly onto the static structural analysis to account for thermal expansion and temperature-dependent material behaviour. By transferring the thermal results rather than applying simplified temperature loads, the combined effect of mechanical and thermal loading could be assessed more realistically.

This sequential approach reflects standard CAE practice, where thermal analyses are used to generate operating conditions for structural evaluation rather than as standalone predictive tools.

8. Static Structural Analysis

8.1. Importing of Loads

Mechanical loads applied in the static structural analysis were derived directly from the preceding kinematic and thermal studies. The reaction moment extracted from the rigid dynamics analysis was imported as an equivalent torque load acting on the fan head, representing the operational resistance encountered during steady-state rotation. In addition, the temperature field obtained from the thermal analysis was mapped onto the structural model to account for thermal expansion effects.

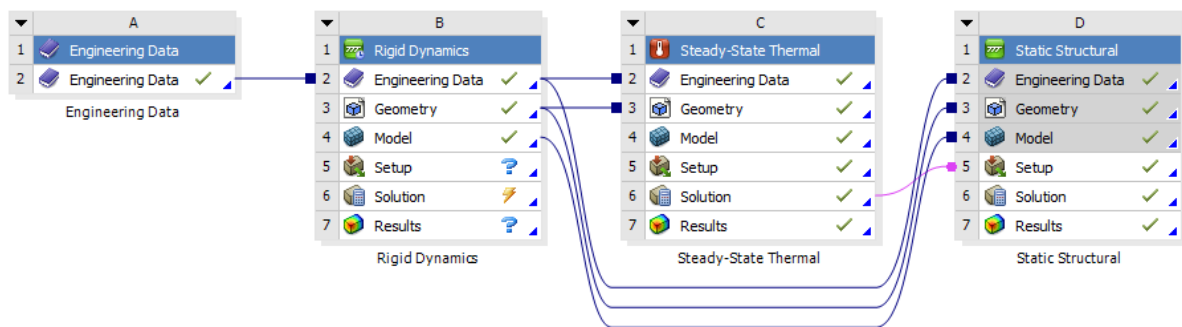


Figure 11: Connecting All Studies to the Static Structural Study

To represent aerodynamic loading, an inferred pressure load was applied to the fan blade surfaces. This pressure approximates the resistance exerted by airflow on the rotating blades and provides a simplified representation of fluid–structure interaction without the need for explicit CFD modelling. Gravity was also included to represent the self-weight of the component.

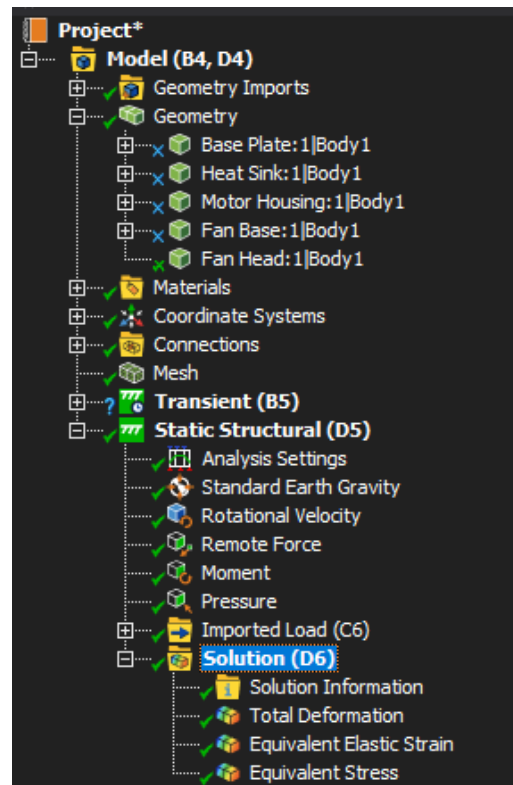


Figure 12: Static Structural Mechanical Set Up Tree

8.2. Constraints, Contacts and Solver Settings

To prevent rigid body motion while avoiding excessive constraint stiffness, the weak springs stabilisation option within ANSYS was employed. This approach introduces minimal artificial stiffness to unconstrained degrees of freedom, allowing the system to reach static equilibrium without significantly influencing stress or deformation results. The use of weak springs when analysing components that are partially constrained or where fully representative supports are difficult to define.

Contacts within the model were simplified using bonded contact definitions to ensure reliable load transfer and solver convergence. This approach avoids numerical instability associated with complex contact behaviour while remaining appropriate for assessing global structural response. A linear static solver was used, with small deformation assumptions considered valid given the expected elastic behaviour of the component.

8.3. Structural Results

The static structural analysis produced distributions of total deformation, equivalent (von Mises) stress, and elastic strain within the fan head. The results were used to identify regions of elevated stress and potential structural weakness under combined mechanical and thermal loading. Maximum stress levels were evaluated relative to the material yield strength to confirm elastic behaviour, while deformation magnitudes were assessed to ensure that functional integrity would be maintained during operation.

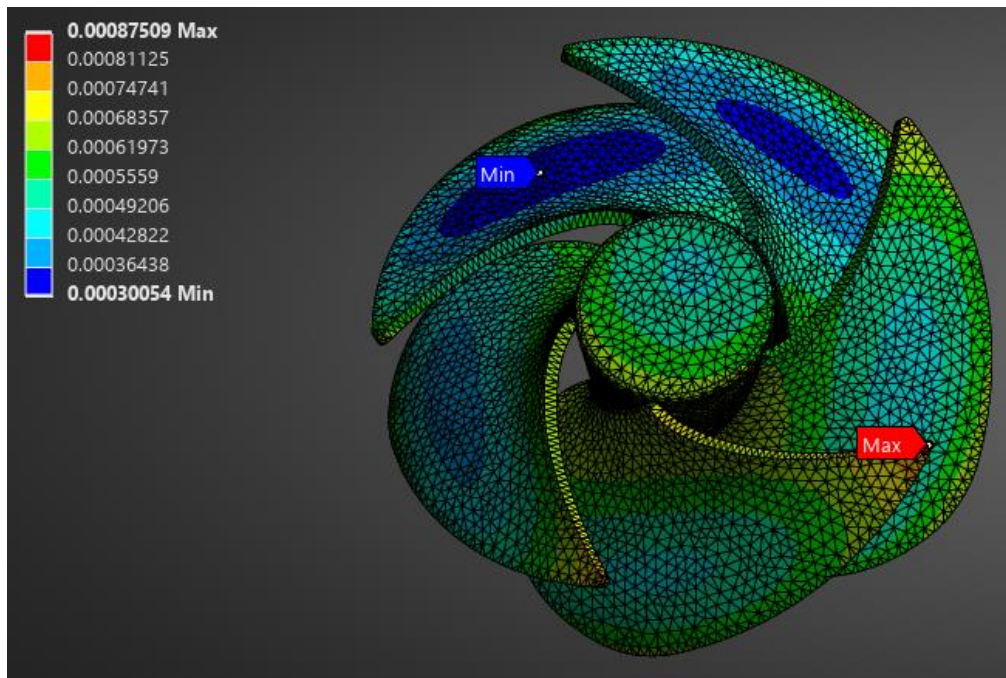


Figure 13: Total Deformation of Fan Head in Metres

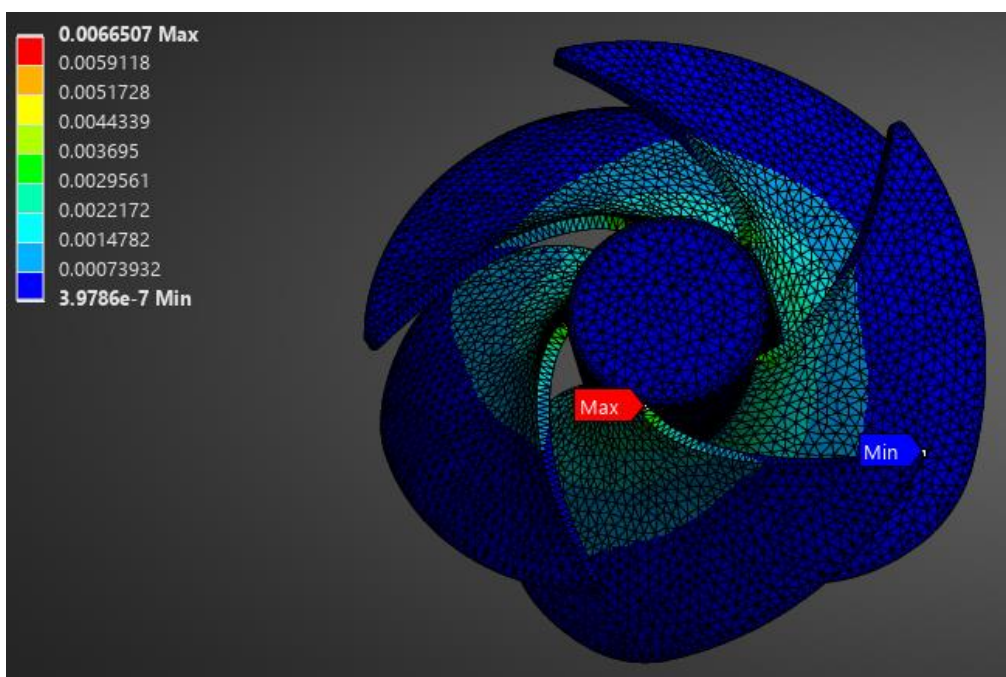


Figure 14: Equivalent Elastic Strain of Fan Head in Metres

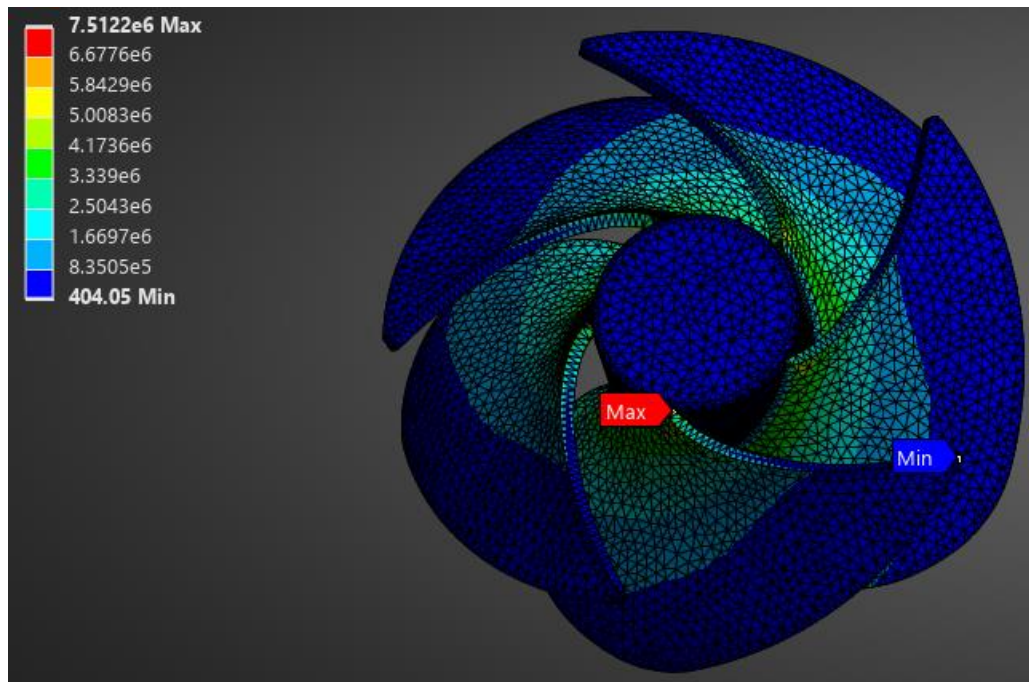


Figure 15: Equivalent Stress in Fan Head in Pascals

9. Design Iteration and Optimisation

9.1. Identification of Critical Regions

Results from the static structural analysis identified the primary region of elevated stress at the interface between the fan blades and the central fan hub. This region experiences the combined effects of centrifugal loading from rotation, aerodynamic pressure acting on the blade surfaces, and thermal expansion. Stress concentrations were consistently observed around the blade root fillets and the blade–hub junction, indicating that this area governs the structural performance of the fan head.

9.2. Design Modifications and Rationale

Based on the identified stress concentrations, the fan head geometry was modified to improve load transfer at the blade–hub interface. The modifications focused on locally reinforcing the blade root region by increasing material thickness and smoothing geometric transitions between the blades and the central hub. These changes were intended to reduce stress concentrations by increasing local stiffness and improving stress distribution without significantly increasing overall mass.

The design modifications were deliberately limited in scope to preserve the original functionality and aerodynamic form of the fan while demonstrating targeted, CAE-informed optimisation.

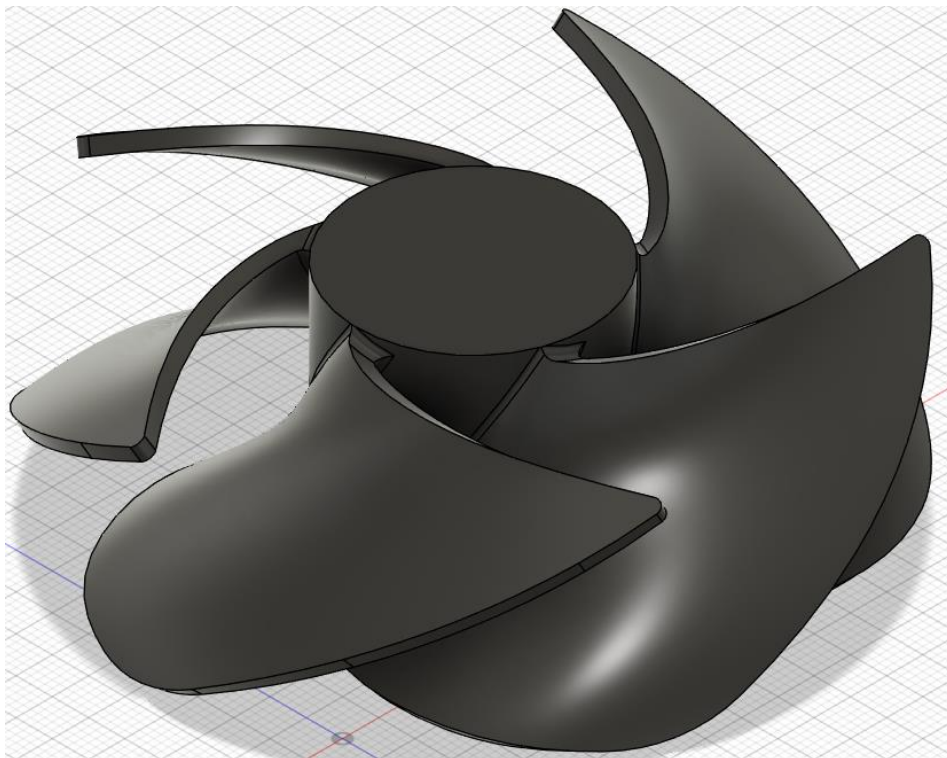


Figure 16: Improved Fan Head Design

9.3. Analysis of Updated Design

Following the geometric modifications, the kinematic, thermal, and static structural analyses were repeated using the same modelling assumptions, boundary conditions, and loading definitions as applied to the original design. Maintaining consistent analysis settings ensured that any observed changes in structural response could be attributed directly to the design modifications rather than differences in simulation setup.

9.4. Performance Comparison

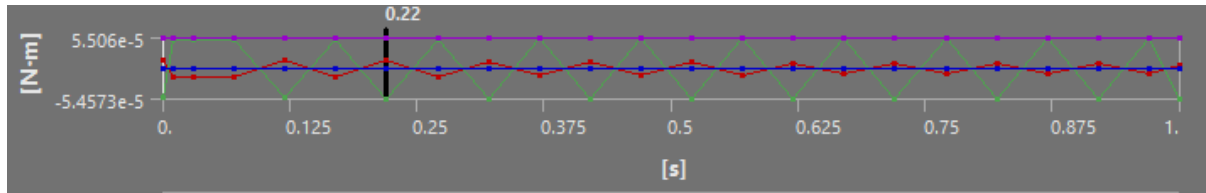


Figure 17: New Total Moment from Rotation

Maximum Value Over Time	
X Axis	1.5866e-005 N·m
Y Axis	5.4537e-005 N·m
Z Axis	1.5534e-024 N·m
Total	5.506e-005 N·m
Minimum Value Over Time	
X Axis	-1.5782e-005 N·m
Y Axis	-5.4573e-005 N·m
Z Axis	-5.1936e-025 N·m
Total	5.506e-005 N·m

Figure 18: Updated Min and Max Total Moment

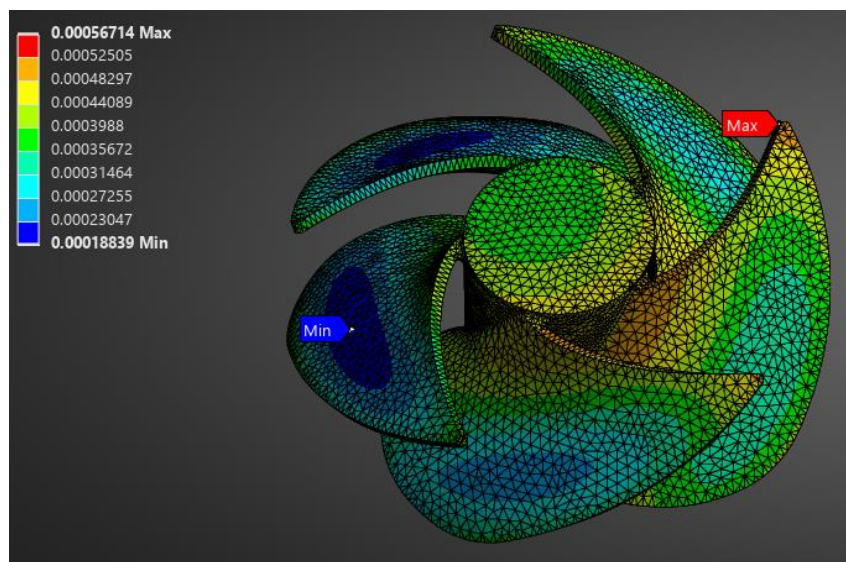


Figure 19: Updated Total Deformation of Fan Head in Metres

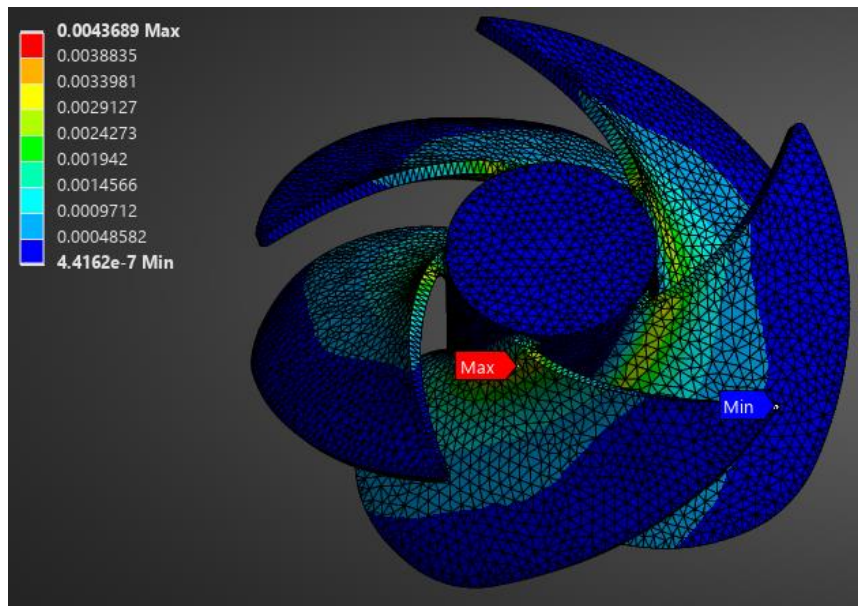


Figure 20: Updated Equivalent Elastic Strain of Fan Head in Metres

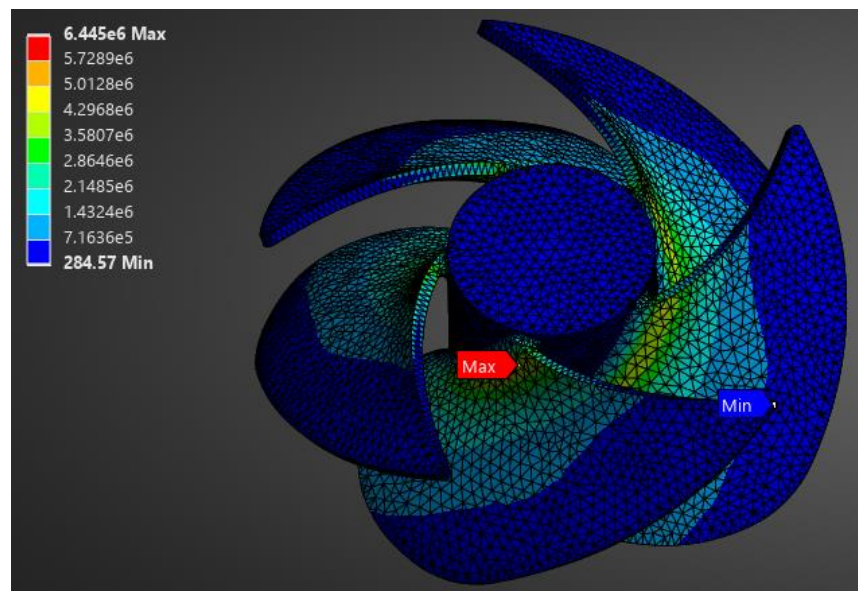


Figure 21: Updated Equivalent Stress in Fan Head in Pascals

Comparison of the original and updated designs demonstrated a measurable reduction in maximum equivalent stress within the critical regions of the fan head, while overall deformation remained within acceptable limits. The mass increase associated with the design modification was minimal relative to the improvement in structural performance, indicating an effective optimisation outcome.

These results confirm that the CAE-driven design iteration successfully improved structural behaviour under combined mechanical and thermal loading. The comparison also highlights the usefulness of CAE tools for identifying critical regions and guiding targeted design improvements, while reinforcing the need to interpret results within the context of modelling assumptions and simplifications.

10. Validation and Sensitivity Studies

10.1. Simplified Analytical Validation Case

To assess the reliability of the CAE results, a simplified analytical validation case was considered. A basic cantilevered beam model was used to represent a fan blade subjected to a uniformly distributed pressure load, providing a closed-form solution for bending stress and tip deflection using classical beam theory. Although this model does not capture the full three-dimensional geometry of the fan blade, it provides a useful reference for validating trends in deformation and stress magnitude.

The analytical solution assumes linear elastic behaviour, small deformations, and uniform material properties, consistent with the assumptions applied in the static structural analysis.

10.2. Software vs Analytical Comparison

Results obtained from the simplified analytical model were compared qualitatively with the CAE results. Both approaches predicted maximum stress occurring at the blade root, where bending moments are greatest, and deformation increasing towards the blade tip. While the absolute magnitudes differed due to geometric simplification and idealised boundary conditions in the analytical model, the agreement in stress distribution trends supports the validity of the CAE results.

10.3. Mesh Independence Study

A mesh sensitivity study was conducted to evaluate the influence of element size on the structural results. The fan head component was analysed using coarse, medium, and fine meshes, and the resulting maximum equivalent stress values were compared. As mesh density increased, changes in peak stress values reduced, indicating convergence towards a mesh independent solution.

Based on this study, a mesh density was selected that provided a suitable balance between solution accuracy and computational efficiency. This approach ensured that the reported results were not unduly influenced by discretisation error.

10.4. Boundary Condition Influence Study

The influence of boundary condition selection was examined by varying constraint definitions and load application methods within reasonable limits. Changes in constraint stiffness and load distribution were found to affect absolute stress values, particularly near constrained regions, while overall stress patterns and critical regions remained consistent.

This sensitivity highlights the importance of carefully defining boundary conditions in CAE analyses and reinforces the need to interpret results in a comparative rather than

absolute sense. The study confirms that, despite sensitivity to boundary conditions, the identified critical regions and observed improvements following design iteration remain robust.

11. Assessment of CAE Tools and Results

11.1. Interpretation of Results and Engineering Meaning

The CAE results obtained in this study provide insight into the structural and thermal behaviour of the fan head under representative operating conditions. The static structural analysis showed that stresses are concentrated at the blade–hub interface, reflecting the expected load path where centrifugal and aerodynamic forces are transferred from the blades into the central hub. The deformation patterns and stress distributions are therefore physically consistent with the function of the component.

Thermal results indicated a relatively uniform temperature distribution within the fan head under the applied convection conditions, suggesting that thermal gradients contribute less significantly to structural response than mechanical loading in this case. When combined within the static structural analysis, the thermal and mechanical loads produced stress and deformation levels that remained within the elastic range of the selected material. These outcomes suggest that the fan head design is structurally adequate under the defined operating conditions, while also identifying regions suitable for targeted reinforcement.

11.2. Limitations, Uncertainty, and Modelling Trade-offs

The results obtained in this study are subject to limitations arising from modelling assumptions and numerical simplifications. Boundary conditions, contact definitions, and load representations were idealised to ensure solver stability, which may influence absolute stress and deformation values. Thermal and aerodynamic effects were simplified through convection and inferred pressure loads rather than fully resolved fluid modelling.

As a result, the CAE outputs should be interpreted as indicative of trends and relative performance changes rather than exact representations of real-world behaviour. These trade-offs are consistent with early-stage design analysis, where CAE is used primarily to guide design decisions rather than provide definitive predictions.

11.3. Lessons for Real World Design Decisions

This study highlights the role of CAE as a decision-support tool within the engineering design process. The analyses successfully identified critical regions within the fan head and guided targeted design modifications that improved structural performance. However, the sensitivity of results to boundary conditions, contact definitions, and modelling assumptions demonstrates that engineering judgement is essential when interpreting CAE outputs.

In real-world design practice, CAE would typically be used in conjunction with experimental testing and empirical data to refine models and validate predictions. The

findings of this study reinforce that CAE is most effective when applied iteratively, with an understanding of its limitations, and when results are used to inform design direction rather than to provide definitive performance guarantees.

12. Conclusions

This report demonstrated the application of Computer Aided Engineering tools to the analysis and iterative improvement of a CPU fan and heatsink assembly. A structured CAE workflow was employed, combining kinematic, thermal, and static structural analyses to evaluate the behaviour of a selected component under representative operating conditions.

The results showed that CAE is effective for identifying critical regions, understanding load paths, and guiding targeted design modifications. In particular, stress concentrations at the blade–hub interface of the fan head were successfully identified and reduced through design iteration. Validation and sensitivity studies highlighted that while CAE results are influenced by modelling assumptions, boundary conditions, and mesh definition, they provide reliable insight into performance trends and relative improvements.

Overall, this work confirms that CAE tools are valuable for supporting engineering design decisions when used with appropriate simplifications and engineering judgement. The study also highlights the importance of critically assessing results and recognising the limitations of computational models when applying CAE to real-world engineering problems.

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14. Appendices