Solid Modeling and Ansys-Based Analysis for Lightweight Transmission Pulley Design in Washing Machines

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Abstract: Enhancing the energy efficiency and effectiveness of appliances like washing machines requires lowering the weight of moving elements. The transmission pulley of a washing machine was selected for a case study using a combination of solid modeling and finite element analysis. ANSYS Workbench was used to build a parametric solid model which underwent rigorous simulation. In the simulation static structural analysis of the model identified stress concentrations and deformation for the given operational loads, while modal analysis provided the natural frequencies to avoid resonance. Using these results, the pulley was reshaped using topological optimization for material removal from low-stress regions. The last verified design underwent performance analysis and achieved significant weight reduction. This case study illustrates a systematic approach for component lightweighting which leads to material and manufacturing costs savings, and operational efficiency improvements in washing machines.

# Introduction

Value engineering is a critical strategic investment for achieving technological leadership within any industry. As SuneelPandita, AVP and Head of Mechanical Engineering Design at KPIT Cummins, notes, it is a fantastic process that triggers a complete system overhaul, encompassing alternative designs, new materials, rigorous verification for strength and safety, and innovative manufacturing and testing processes. From his experience, value engineering frequently leads to disruptive innovations and the development of environmentally friendly systems and technologies [1-4]. This systematic methodology is dedicated to improving the "value" of goods, products, and services through a thorough examination of function, where value is explicitly defined as the ratio of function to cost. Consequently, value can be enhanced either by improving the product's function or by reducing its cost. A core principle of this approach is that basic functions must be preserved and not diminished in the pursuit of value improvements. In practical terms, this translates to either saving costs or adding value to functions, which in the context of this project, means saving material and reducing the total cost of a washing machine [5-9].

This project specifically aims to achieve material savings in the transmission pulley of a cloth washing machine, a central component in the appliance's assembly. The pulley in question belongs to the well-known home appliance manufacturer IFB Industries. It is fitted onto the agitator and spin basket shaft and is coupled with the motor via a belt drive, functioning as the primary power-transmitting element for both the agitation and continuous spin modes of operation. Currently manufactured using aluminum casting, the part is produced in high volumes, with an average of one hundred thousand units made annually for 5 to 6 kg variant machines. Given this scale, even a small amount of material saved per unit will have a major impact on the product's overall total cost, making it an ideal candidate for value engineering analysis and redesign [10-13].

Washing machines are broadly classified into two main types: top-loading and front-loading. Top-loading machines are most popular in regions like the USA, Canada, and Australia, spin on a vertical axis and are loaded from the top. They are categorized by their load capacity, typically ranging from 5 kg to 7 kg. Inside, a vertically-mounted perforated basket with a central agitator uses a pulling and swirling motion to clean clothes suspended in water [15-19]. While effective for general laundry, this design is less suited for large items like pillows, which may float without circulating, and the aggressive agitator action can be harsh on delicate fabrics. This design differs significantly from the other major classification of machines.

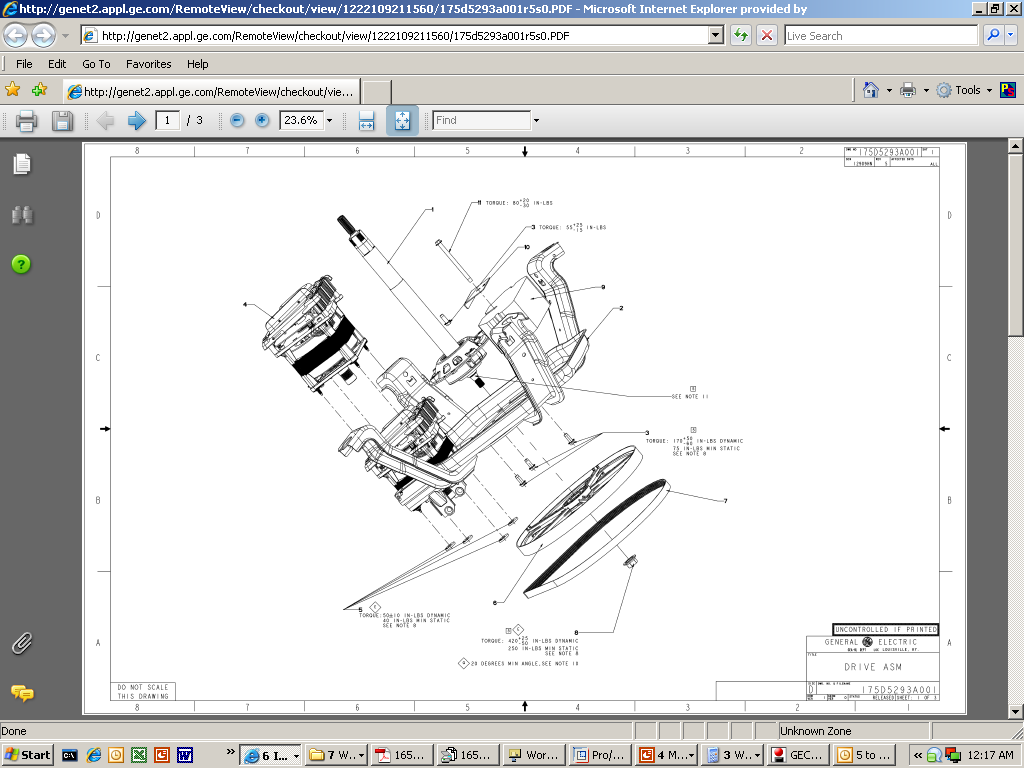


Fig.1 Washing Machine Assembly

The alternative, front-loading washing machines, are predominant in Europe, the Middle East, and India. These machines operate on a horizontal axis and are loaded through a door on the front of the unit. The wash action is supplied by the gravity-assisted tumbling of clothes inside the drum; paddles lift the laundry and then drop it, flexing the fabric weave to force water and detergent through the load. This method requires significantly less water than top-loading models, as the clothes only need to be moistened rather than fully suspended. Consequently, front-loaders generally use less soap and energy. They are also available in various load capacities, commonly from 5 kg to 6 kg. Figure 1.1 provides an exploded view of a full washing machine assembly, illustrating the interaction of the transmission pulley with other components and clarifying its contact points and functional requirements within the system [20-22].

Cost Saving of Transmission Pulley in order to gain cost advantage, achieved through design optimization by modifying shape and size of Pulley. Redesign the pulley to reduce the material usage by 10%. The scope of this project is applicable to range of Washing machine capacity of 5 kg to 6 kg with 5spokes. This Methodology can also be used in any application which requires Pulley / Flywheel.

Alphonse J. Dell’Isola and D.L. Younker establish the foundational principles of Value Engineering (VE), defining it as a systematic methodology to enhance product value through a rigorous examination of function, where value is quantified as the ratio of function to cost. This principle of maximizing function while minimizing cost is the core objective of the present project, guiding the effort to reduce material in the transmission pulley without compromising its performance. The work of John Dixon further contextualizes this goal by identifying the pulley's critical role as the main power-transmitting element for both agitation and continuous spin operations in a washing machine. This functional requirement is critical; any redesign must allow the component to continue enabling the drum's slow, bi-directional rotation during agitation and high-speed spinning. Therefore, the value engineering process is not simply trimming costs; it is focused on enhancing a high-volume part whose design efficiency greatly impacts manufacturing costs and product sustainability on an aggregate level [23-28].

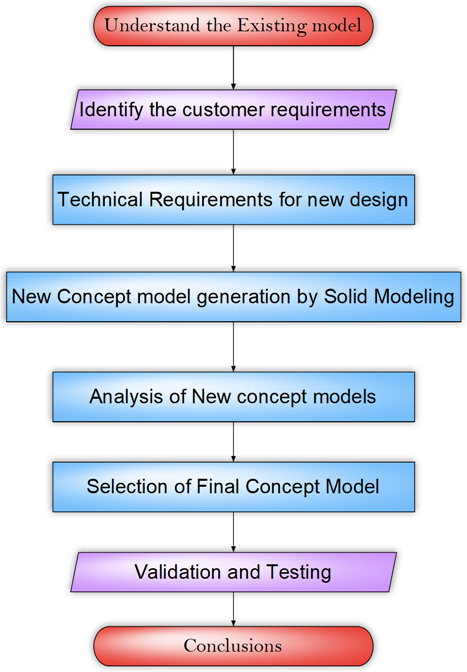


Fig. 2 Process flow chart

Any redesign of a pulley continues to depend on its structural stability, and previous analyses of failures offer invaluable perspectives toward a new design. The work done by J. A. Martins and I. Ferreira, who studied the fracture and collapse of heavy-duty pulleys on conveyor systems, offers critical insights on failure modes. Their analysis of the failure zones and crack propagation captured on x-ray revealed these failures were a result of excessive high concentrated stresses where the sharp geometric edges initiated. This reinforces one of the primary design rules to eliminate stress risers which requires to smooth transitions instead of sharp corners in the new pulley design. Additionally, the force analysis provided by Joseph Edward Shigley and John Dixon and later elaborated on by M. Ravikumar and AvijitChattopadhyay has clarified the complex loading phenomenon. In addition to the equatorial ring, the pulley arms encounter axial and tangential force, meaning that any alteration to the spoke geometry and cross-sectional shape will demand a structural analysis to match these specific loading conditions to be considered structurally safe under operational stress [29-33].

For operational stress simulation and design validation, the Finite Element Method (FEM) is used. An integral analysis approach for conveyor pulleys published by M. Ravikumar and AvijitChattopadhyay provides a rigorous methodology for the analysis of the rim and centrifugal and axial loads on the spokes. SOLID92 is the element type of choice for this analysis because of its ability to model complex geometries. As analyzed, this element is a quadratic displacement element which helps greatly with irregular meshes from CAD models. SOLID92 is characterized by ten nodes with three degrees of freedom for each node, which yields accurate stress calculations. Its ability to simulate plasticity, large deflection, and large strain is critical for a total simulation to predict with confidence that the optimized design of the pulley will operate without failure under dynamic loads.

# Materials and Methods

## Materials

The project began with a detailed study of the existing transmission pulley model used in IFB's 5 to 6 kg washing machines. This component, featuring a five-arm design with a flat rim for belt coupling and a central hub with pockets for engaging the spin basket armature, was identified as the primary scope for material optimization. The functional requirements were paramount; the pulley must reliably transmit power for both the slow, bi-directional agitation and the high-speed spin cycles with a 12:1 to 16:1 reduction ratio. Crucially, any redesign had to satisfy key consumer demands for long-term reliability, performance, and quiet operation, which translated into specific technical requirements [34-36].

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Fig. 3 Existing Pulley Model

These included maintaining strength to withstand an 800 rpm operational speed under significant loads (311N & 1.7KN), controlling deflection and runout, ensuring a high section modulus, and avoiding resonance noise by carefully considering the number and angle of spokes. Furthermore, the new design had to pass rigorous durability tests simulating over a decade of use, including accelerated braking, heavy unbalanced spinning, and continuous agitation, all while keeping operational noise below 65 dBa [37-39].

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Fig 4. Cross Section of Engaged Diagram

To meet these challenging objectives, three new concept models were generated using Pro/ENGINEER solid modeling software.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| First CAD Model | Second CAD Model | Third CAD Model |
| Fig 5 – (A) (B) (C) Designed CAD Models | | |

The first concept featured three spokes with an "H" cross-section, achieving a 7% weight reduction. The second concept also used three spokes but with a "+" cross-section for potentially greater bending resistance, yielding a more substantial 14% weight saving [40-45]. A third concept employed a "+" cross-section but with five spokes, offering an 8% reduction. A critical analytical foundation was established by calculating the forces acting on the existing pulley, primarily centrifugal force on the rim and a combination of bending and axial loads on the spokes.

# Description: http://web.mit.edu/calculix_v1.6/CalculiX/ccx_1.6/doc/ccx/img91.png

Tetrahedral Element

Fig 6 Soild92 Geometry

Using material properties for Die Cast Aluminum 380 (Ultimate Tensile Strength: 317 MPa, Yield Strength: 158 MPa), hand calculations for the existing model determined a total stress of 111.2 MPa at the hub, resulting in a Factor of Safety of 1.74, which served as a critical benchmark for evaluating the new concepts.

Each concept model was subjected to rigorous Finite Element Analysis (FEA) in ANSYS Workbench to validate its performance under operational loads. The models were meshed using the SOLID92 element, a 10-node tetrahedral element chosen for its accuracy in modeling complex geometries and its capability to handle large deflections. The boundary conditions applied a fixed support at the rim's engagement point, a 45 N-m torque at the hub center, a rotational velocity of 630 rpm to account for centrifugal forces, and standard earth gravity. The analysis yielded clear results: the 3-spoke "H" design exhibited a very low maximum von Mises stress of 25 MPa, leading to a high Factor of Safety of 6.32. In contrast, the 3-spoke "+" design showed a higher stress of 39 MPa (FOS: 4.05), and the 5-spoke "+" design performed the worst with a critical stress of 67 MPa (FOS: 2.3).

Table: 1 Aluminium Specifications [46-48]

|  |  |
| --- | --- |
| Modulus of Elasticity | 71 GPa |
| Modulus of Rigidity | 26.5 GPa |
| Ultimate Tensile Strength | 317 MPa |
| Yield Strength | 158 MPa |
| Elongations % in 50 mms | 2.5 |
| Ultimate shearing Strength | 193 MPa |
| Endurance Limit | 139 MPa |
| Poisson’s Ratio | 0.33 |

# Results and Discussion

Based on a comprehensive review of the FEA results, the 3-spoke "H" cross-section design was selected as the finalized concept.

## THREE SPOKE – “H” DESIGN

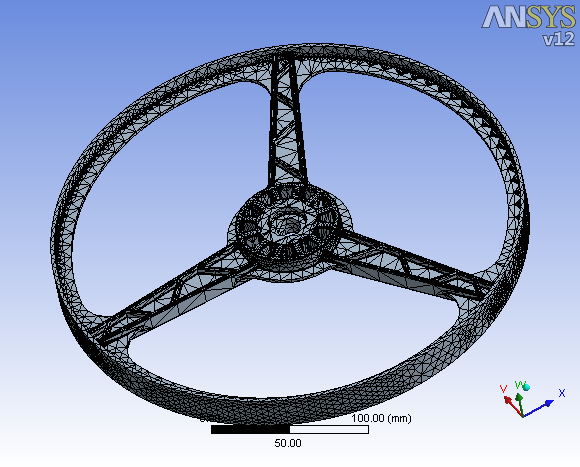




Fig. 7 Concept-1 FE Mesh Model

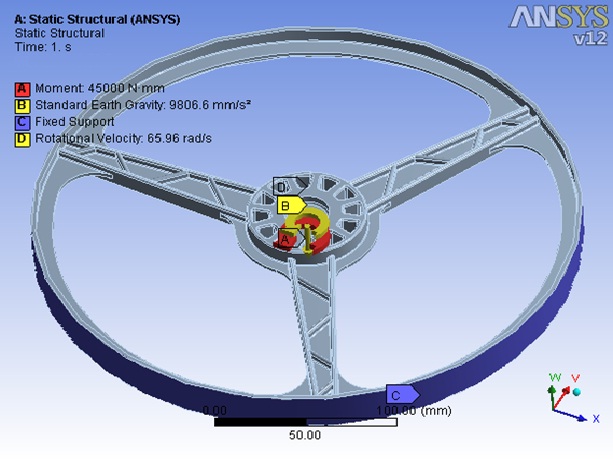


Fig. 8 Concept-1 Boundary Condition

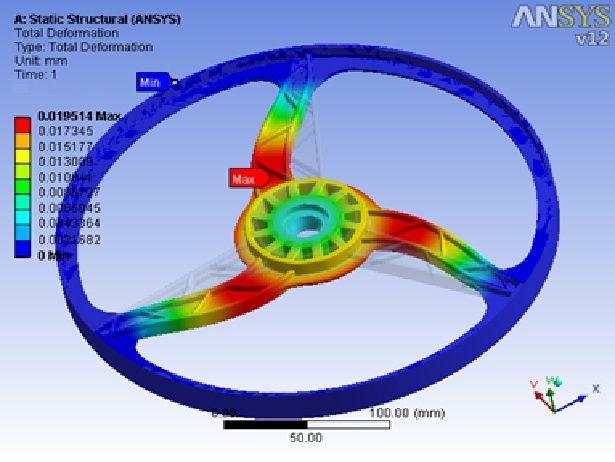


Fig. 9 Concept-1 Displacement

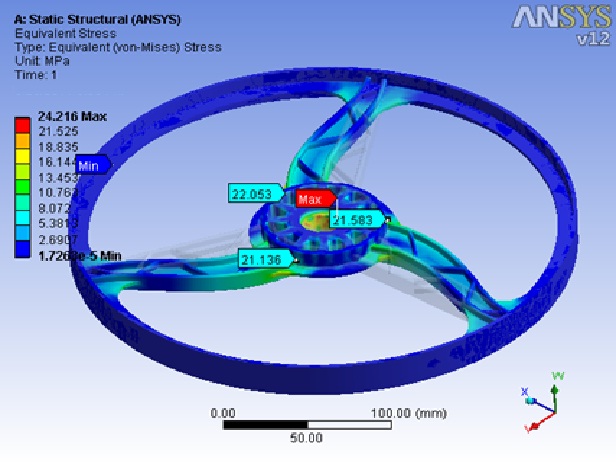


Fig. 10 Concept-1 vonMises Stress

The above Fig 4.1, 4.2, 4.3 & 4.4 is Analysis Result of First CAD model with “H” design Variable section with 7 % weight reduction. Maximum von Mises Stress at fixed end of spoke that is 24.26MPa. Boundary condition is fixed support is at Rim end, 45 N-m Torque applied along axis Pulley, second one Angular Velocity of 65.96 rad/sec at surface of pulley [49-52].

## THREE SPOKE – “+” DESIGN

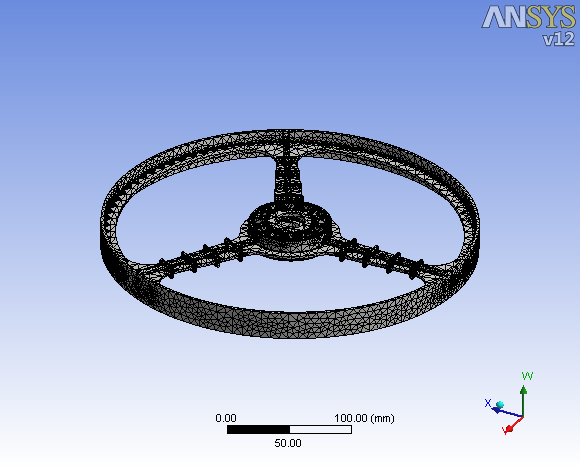
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Fig. 11 Concept-2 FE Mesh Model

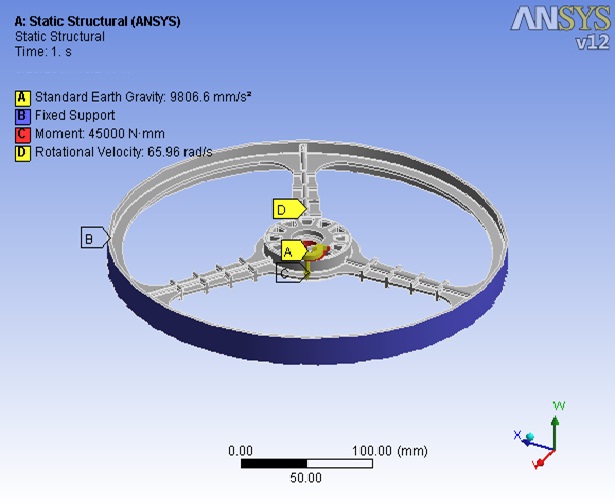
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Fig. 12 Concept -2 Boundary condition

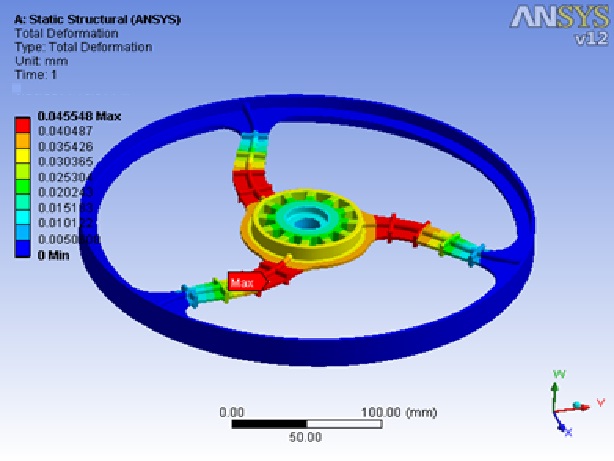
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Fig 13 Concept -2 Displacement

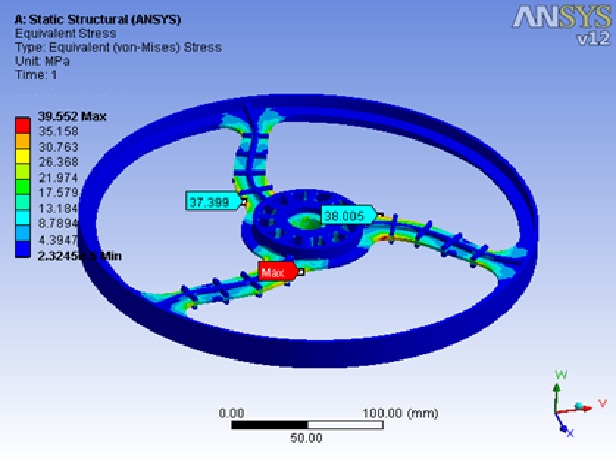
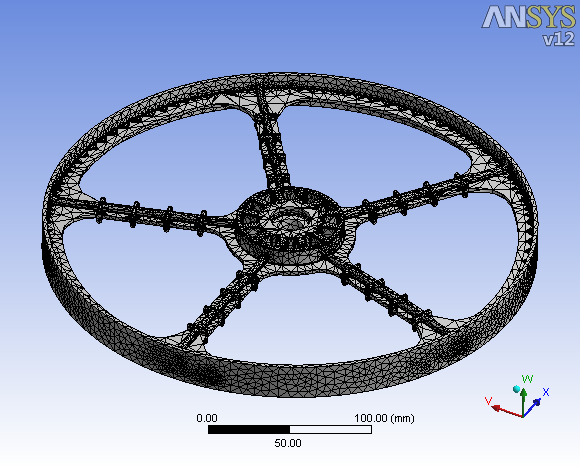
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Fig. 14 Concept-2 von Mises Stress

The above Fig 4.5, 4.6, 4.7 & 4.8 is Analysis Result of Second CAD model with “+” design Variable section with 14 % weight reduction. Maximum von Mises Stress at fixed end of spoke that is 39.552MPa. Boundary condition is fixed support is at Rim end, 45 N-m Torque applied along axis direction and Angular velocity 69.56 rad/sec applied also applied.

## FIVE SPOKES – “+” DESIGN

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Fig. 15 Concept-3 FE Mesh Model

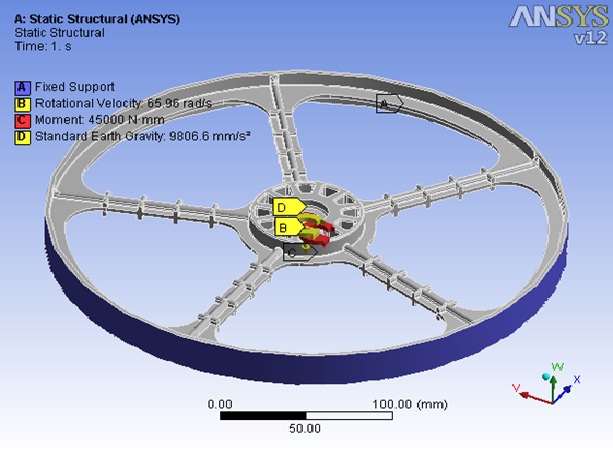
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Fig. 16 Concept -3 Boundary Condition

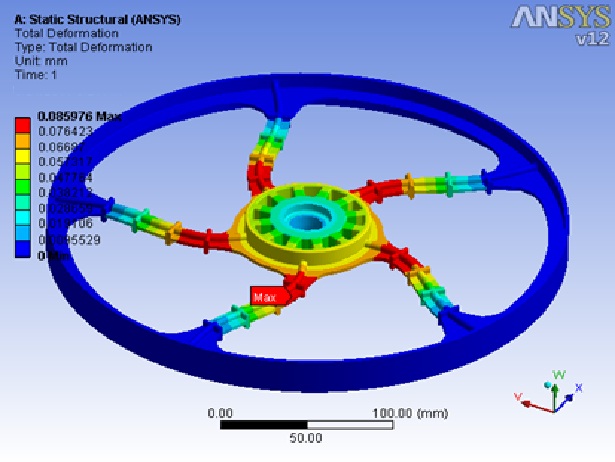
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Fig. 17 Concept-3 Displacement

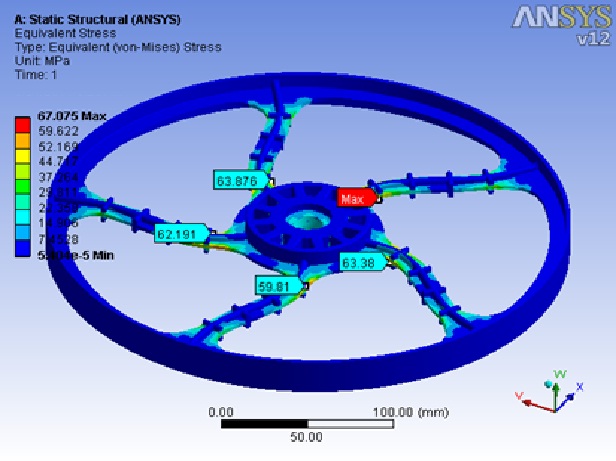
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Fig. 18 Concept -3 von Mises stress

The above Fig 4.9, 4.10, 4.11 & 4.12 is Analysis Result of Third CAD model with “+” design Variable section with 8 % weight reduction. Maximum von Mises Stress at fixed end of spoke that is 67.075MPa. Boundary condition is fixed support is at Hub end and other side Rim end both forces applied one is along axis direction, second one tangential to spoke.

The final result have been list in below table understand clearly which concept is better for future progress in this project.

Factor of Safety = Ultimate Yield Strength/ Max.VonMises Stress (1)

Although its 7% weight reduction was more modest than the 14% offered by the 3-spoke "+" design, its significantly lower stress value and consequently higher Factor of Safety were deemed far more critical for ensuring long-term reliability and durability. The extreme stress on the 5-spoke "+" model rendered it unacceptable. The superior performance of the "H" design was attributed to its section properties, which more effectively resisted the combined bending and axial loads. Furthermore, an additional optimization opportunity was identified at the hub. A proposal was made to remove material circumferentially from the area below the engagement tooth pockets, reducing the pocket diameter from 38.68mm to 31.75mm. This change would yield further weight savings without disturbing the critical fitment and functional surfaces of the teeth, pushing the overall material reduction beyond the initial 7%.

Table 2 Maximumvon Mises Stress

|  |  |  |  |
| --- | --- | --- | --- |
| **TYPE OF MODEL** | **Max. von Mises Stress (MPa)** | **Factor of Safety with Yield Strength** | **% WEIGHT REDUCTION** |
| 3 SPOKES “H” DESIGN PULLEY | 25 | 6.32 | 7 % reduction |
| 3 SPOKES “+” DESIGN PULLEY | 39 | 4.05 | 14% reduction |
| 5 SPOKE “+” DESIGN – PULLEY | 67 | 2.3 | 8% reduction |

The final phase of the project involved validating the optimized design through a stringent battery of physical tests designed to simulate a full product lifecycle of ten years. This included an 800-hour Heavy Unbalanced Spin test with off-center loads, a 150-hour Accelerated Braking Action test with rapid start-stop cycles under a 142N load, and a 1250-hour Continuous Agitation test. A critical Noise Test required the new pulley assembly to maintain an average operational noise level at or below the baseline of 65 dBA. Successfully passing these tests was imperative to prove that the value-engineered pulley achieved the core objectives of material and cost savings without any compromise to the functional performance, structural integrity, durability, and acoustic characteristics demanded by the consumer and technical specifications.

# Conclusion

The project commenced with a comprehensive study of the structural behavior of the existing transmission pulley model used in IFB's 5 to 6 kg washing machines. The main goal was to reduce weight substantially on the plated parts referred to as the pulley arm spokes while the critical dimensions and the fitment tolerances of the assembly parts will still be preserved. In pursuit of this goal, three new concept models were created on Pro-E for the evaluation which included “H” cross-section with 3 spokes, “+” cross-section with 3 spokes, and “+” cross-section with 5 spokes. Each of these concepts went through as rigorous analytical and Finite Element Analysis (FEA) as possible to assess the concepts against strict, precise measurements alongside an acceptable safety factor to avoid damage to the washing machine.

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Fig 19 Concept – 1 Fig 20 Concept - 2

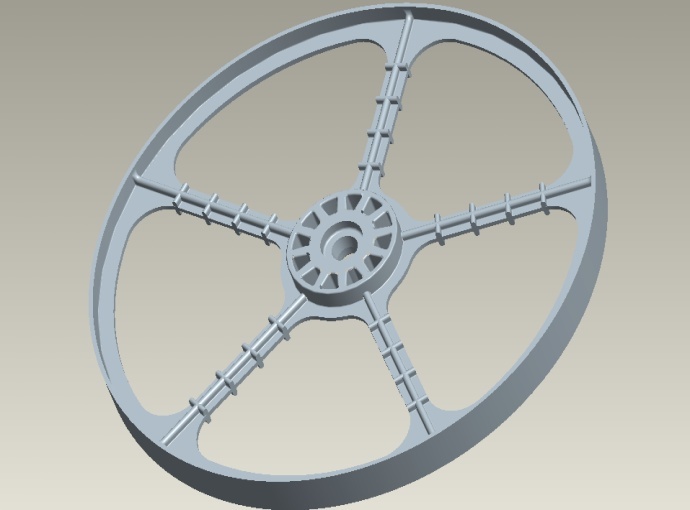


Fig 21Concept - 3

The FEA results gave a straightforward focus toward the best design. The '+' cross-section with 3 spokes model was a no-go because of the very high maximum von Mises stress of 39 MPa, even though it achieved a 14% weight reduction. The '+' cross-section with 5 spokes model was even worse, showing a critical stress level of 69 MPa with only 8% reduction. On the other hand, the “H” cross-section with 3 spokes model seemed to be the best choice, having 7% weight reduction and a considerably lower maximum von Mises stress of 25 MPa. Based on a comparative analysis of all parameters—including stress, volume, section modulus, and factor of safety—this model was selected as the final concept. Furthermore, the analysis indicated potential for additional weight reduction at the hub end. A design optimization was proposed to remove material circumferentially from the area below the engagement tooth pockets, a region away from the critical fitment interfaces, allowing for further mass reduction without disturbing the functional integrity of the teeth and pockets that couple with the armature shaft.

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