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Sketch-Based Multi-Objective Design Study of Engine and Gearbox Seals: A CAE Approach for NVH and Tribological Enhancement

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ABSTRACT: Engine and transmission seals are critical components designed to prevent fluid leakage and block contaminants while contributing significantly to the overall NVH (Noise, Vibration, and Harshness) performance of vehicles. The tribological interactions within these seals can affect their efficacy and durability, necessitating advanced methods for optimization and analysis. This study aims to harness CAE tools for the parametric optimization of engine and transmission seals, focusing on improving both their sealing effectiveness and NVH characteristics. The research seeks to identify and optimize key design parameters that influence the tribological and acoustic performance of seals. By enhancing these characteristics, the study aims to reduce potential noise sources, decrease vibration, and extend the lifespan of the seals under various operational conditions. Utilizing state-of-the-art CAE software, this study conducts finite element analysis (FEA) to simulate the mechanical behavior and tribological interactions of different seal designs under dynamic conditions. Commercial tool is employed for parametric optimization, systematically adjusting variables such as material properties, geometrical dimensions, and contact surface conditions. The study employs a multi-objective optimization approach to balance improvements in NVH performance with the tribological demands of the seals. This methodology not only highlights the critical noise-generating parameters but also provides a quantitative basis for enhancing seal design and performance. The tribological challenges addressed include material wear and friction characteristics, which are influenced by the interaction of seal materials under operational stresses. The design's impact on seal performance is evaluated by balancing forces within seal structures to optimize heat generation and minimize leakage potential, especially under varying temperature condition.

KEYWORDS: CAE, Elastomer, Numerical Simulation, NVH, Optimization, Seal, Tribology

I. INTRODUCTION

The parametric optimization of engine and transmission seals to enhance NVH (Noise, Vibration, and Harshness) and tribological performance is a critical area in automotive engineering. The following review synthesizes the key themes from the existing literature.

1.1. NVH Considerations in Seal Design

Seal design significantly influences NVH characteristics in automotive engines. The NVH performance of seals, especially in the context of their viscoelastic properties, is crucial for ensuring comfort and minimizing operational noise and vibrations. As discussed in the provided documents, different materials exhibit varying damping characteristics, which can either amplify or mitigate noise and vibration at different frequencies [1]. Furthermore, studies like those have shown that materials such as FKM, known for its high damping properties, are more effective in reducing NVH issues compared to others like [2].

1.2. Tribological Performance

Tribological performance, which involves the study of friction, wear, and lubrication, is another critical aspect of seal design. The optimization of these properties ensures the durability and efficiency of engine and transmission systems. The interaction between seal materials and lubricants, especially under varying temperature and pressure conditions,

can significantly affect seal performance and longevity. Materials that exhibit better tribological properties can enhance seal effectiveness and reduce maintenance needs.

1.3. Parametric Optimization Using CAE

Computer-Aided Engineering (CAE) plays a pivotal role in the parametric optimization of seals. By using CAE tools, engineers can simulate various operational conditions to predict the performance of different seal designs before physical prototypes are created. This approach not only saves development time but also helps in refining the design to meet specific performance criteria such as enhanced seal ability, reduced material stress, and optimal flange strength [3, 4]. Techniques such as finite element analysis (FEA) are extensively utilized to analyze the stress distribution and deformation under different loading conditions, which are critical for predicting the seal's operational efficacy and its impact on the overall system's NVH characteristics.

1.4. Integrated Approaches in Seal Design

Recent advancements focus on integrating multiple functionalities into seal designs to address both sealing and NVH issues effectively. For instance, compound isolation designs, which combine materials with high and low damping properties, offer a balanced approach to manage NVH while maintaining good sealing performance [2]. These integrated approaches are becoming increasingly important as automotive systems become more complex and the demands for higher performance and lower emissions grow.

Despite significant advancements, challenges remain in optimizing the materials and designs to achieve the desired balance between NVH reduction and tribological performance. The complexity of interactions under real-world operating conditions often requires ongoing refinement of models and materials. Future research is likely to focus on developing new materials with improved properties and on enhancing the predictive capabilities of CAE tools to better simulate real-world conditions [3].

The valve cover is a component located on the top of a combustion engine. While its primary function being sealing the oil inside the engine from leaking, the valve cover also has the function of attenuating noise caused by engine vibration. Due to its large surface area and relatively small thickness, the valve cover has been identified as one of the major contributors to radiated engine noise [5-6].

Several different designs are used to combine the flange, radial lip seal and static seal components into one module besides reducing the number of parts, this also results in improved sealing reliability. The number of sealing surfaces is reduced, as is the possibility of handling and assembly errors [7-12].

The sealing element to shaft surface geometry was designed based on many years of experience with clamped or bonded PTFE elements. Only the area where the PTFE element is embedded into the thermoplastic material had to be redesigned to accommodate the thermoplastic material. With this it was possible to utilize previous validation test results in the radial lip seal area and to employ a proven dynamic sealing system.

II. SEAL - OVERVIEW SECTION

Seals play an essential role in machinery, primarily designed to maintain lubricants within the system while keeping contaminants out. Their importance escalates in scenarios involving extreme environmental conditions or where high cleanliness standards are essential. By effectively integrating seals with the appropriate bearings and lubricants, it's possible to significantly reduce friction, enhance energy efficiency, and decrease the wear and tear on components [13]. Currently, the automotive industry is undergoing a transformation like never before, driven by heightened environmental consciousness and increasingly rigorous emissions regulations. Seals are crafted for a multitude of components in both conventional and hybrid/electric vehicles, encompassing engines, drivelines, suspensions, and wheel-ends. Fig.1 illustrate the virtual and real seal products and Table 1. Explains various types.

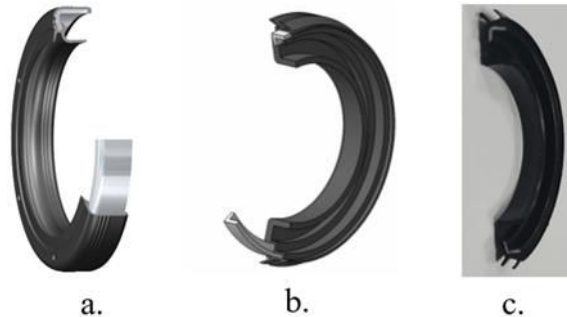


Fig.1. a. Seal available in market [13], b. 3D CAD Design, c. Product cut-section

2.1. Typical Design Concerns in Gasket/Seal Engineering

The design and engineering of gaskets and seals involve addressing multiple concerns that significantly influence their functionality and reliability. Below are elaborated descriptions of typical challenges faced by engineers when designing gasket/seal systems. Refer Table 2. about Typical Design Concerns in Gasket/Seal Engineering.

2.2. Typical Design Variable Concerns in Gasket/Seal NVH & Tribology

This Table 3. Succinctly captures how the coefficient of friction and Shore hardness values of rubber materials affect both NVH characteristics and tribological performance of seal applications.

2.3. Radial shaft seals

Radial shaft seals sit between rotating and stationary components, or two components in relative motion. They have two main parts. One is a cylindrical outer covering with an interference fit that seals statically against the housing bore. The second, a sealing lip, seals dynamically and statically against the shaft. It's sealing edge presses against the counter face surface of the shaft with a defined radial load.

Some radial shaft seal designs have an auxiliary lip that protects the primary sealing lip from dust and other contaminants. A suitable lubricant in the space between the primary sealing lip and the auxiliary lip can reduce wear and delay corrosion. Contaminants that have passed the auxiliary lip will eventually cause damage in the counter face surface area. A build-up of heat can also occur between the two lips, resulting in premature wear.

Radial shaft seals are used in a multitude of applications. Because of the importance of radial shaft seals for the operational reliability and service life of machines and equipment, both seal manufacturers and users are equally interested, to some degree, in standardization. These cover boundary dimensions, tolerances, material specifications, test methods and terminology as well as the basic outside diameter constructions and sealing lip arrangements.

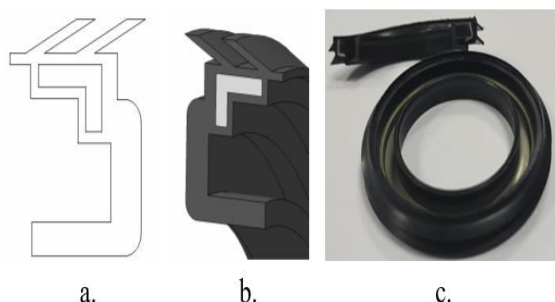


Fig. 2. a. CAD-Cross section b. 3D CAD sectional view, c. Product

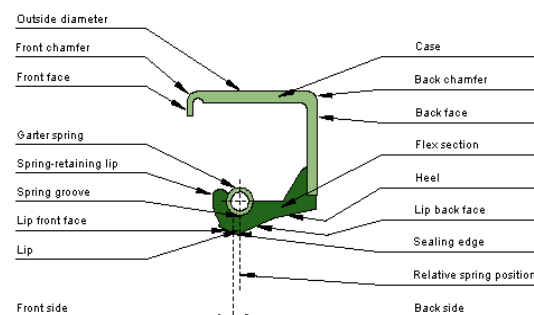


Fig. 3. Seal Section terminology -1 [14]

The terminology used in this chapter is listed for metal-cased seal Figure 3 and for rubber outside diameter seal Figure 4.

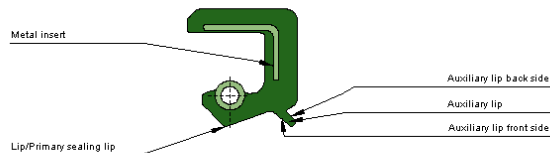


Fig. 4. Seal Section terminology -2 [14].



Fig. 5. Seal in assembly [15]

Radial shaft seals are used between rotating and stationary machine components Figure 5 or between two components in relative motion and consist of two main parts:

- A cylindrical outer covering of sheet steel (case) or an elastomer that has the requisite interference fit to seal statically against the housing bore.
- A sealing lip made of an elastomeric or thermoplastic material that seals dynamically and statically against the shaft. The lip has a sealing edge that is formed by molding, cutting or grinding. It is normally pressed against the counter face surface of the shaft, with a defined radial load, by a garter spring. The edge of the sealing lip and the shaft counter face surface form the most important functional area of a radial shaft seal. The sealing effect of the lip can be enhanced by designing the contact area of the lip with hydrodynamic features.

Radial shaft seal criteria and types of applications are listed in Table 4 & Table 5 respectively.

2.4. SEAL Material CONSIDERATIONS:

Automotive seals are generally manufactured from the materials listed in the Table 6. These materials have characteristics that make them particularly suitable for specific applications. By changing the actual formulation and blending, it is possible to modify the characteristics of the elastomers relative to:

Resistance to swelling	Chemical resistance	Behavior in the cold
Elasticity	Thermal resistance	Gas permeability

Because the above mentioned factors also influence the service life and performance of the seal, the information contained in the table Chemical resistance can only be considered as a rough guide.

2.5. Cases and inserts

Metal cases and reinforcements for radial shaft seals are manufactured standard from deep-drawn carbon sheet steel. The exposed surfaces are treated to protect them from corrosion during normal handling and storage. Radial shaft seals that will be used in corrosive environments can also be designed with a stainless steel case on request.

III. THE CAE APPROACH TO GASKET AND SEAL DESIGN OPTIMIZATION

The optimization of gasket and seal designs through Computer-Aided Engineering (CAE) is a structured process in Figure 6. that encompasses two primary stages, ensuring that each seal or gasket not only meets the requisite design criteria but also aligns with manufacturing feasibility and operational durability.

3.1. Stage One: Cross-Section Evaluation and Optimization

In the initial stage, the focus is on evaluating the cross-sectional design in Figure 7. and Figure 8. of the gasket or seal. This evaluation is crucial as it involves assessing the pressure versus compression characteristics of the gasket. These characteristics must align with predefined design targets that dictate the necessary performance standards for seal ability and mechanical integrity.

If the initial evaluation reveals that the characteristics are suboptimal, modifications are made to the cross-sectional shape of the gasket or seal. This iterative process of refinement continues until the design not only meets but exceeds the specified targets. Subsequently, the optimized design undergoes further enhancements to minimize material usage without compromising the seal's quality and effectiveness. This step is vital for cost management and environmental sustainability, reducing waste and the overall carbon footprint associated with the production of the seals [16].

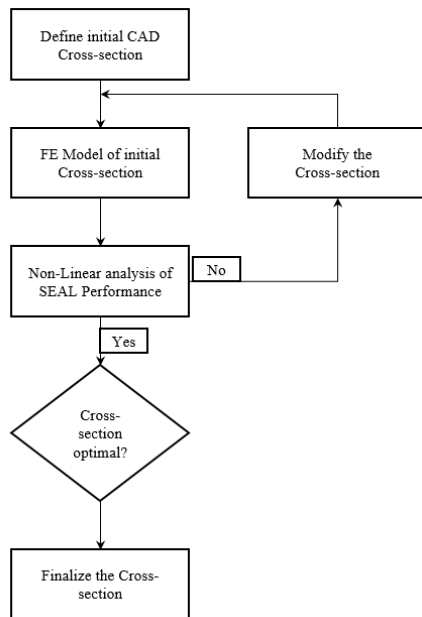


Fig. 6. Traditional Cross section evaluation process,

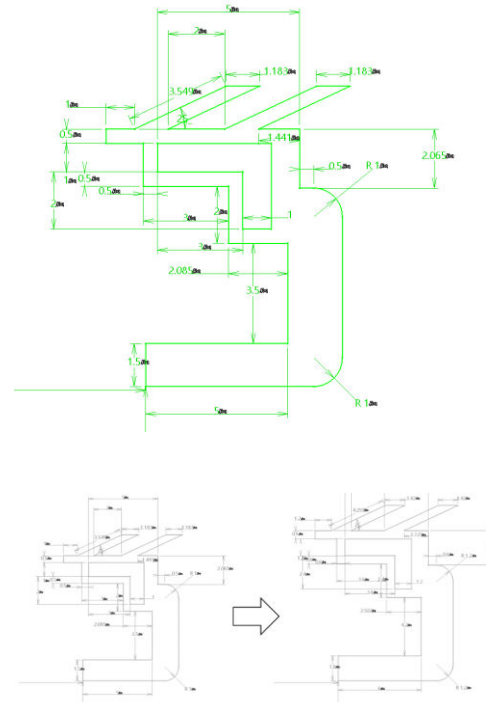


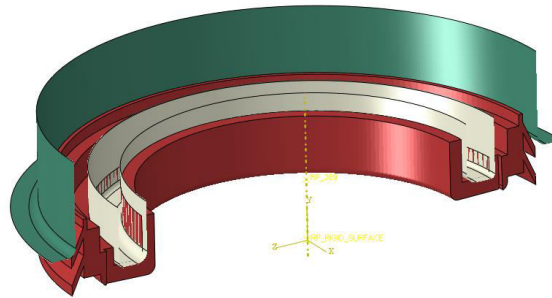
Fig 7. Seal Section Sketch – constrained-1,

3.2. Stage Two: Whole Assembly Evaluation

Once the cross-sectional design is finalized and optimized, the second stage involves a comprehensive evaluation of the gasket or seal within the context of the entire assembly. This assembly consists of the gaskets or seals, flanges, and securing bolts, forming a complete system that must be rigorously tested for overall functionality.

The evaluation process in this stage is multifaceted, focusing on:

- Seal ability: Ensuring that the assembly maintains a tight seal under various operational conditions to prevent leaks.
- Flange Strength: Assessing whether the flanges can withstand the maximum clamp loads without yielding or breaking.
- Long-Term Performance: Evaluating the durability of the assembly, considering factors like material creep — where materials may deform permanently under long-term stress — which can affect the integrity of the seal over time.

**Fig.8. 3D Seal Section**

This stage often reveals areas where further modifications are necessary, whether in the design of the gasket or seal, the flanges, or even the bolt patterns and tightening protocols. Each modification is carefully analyzed, and the assembly is re-evaluated to ensure that all performance criteria are met robustly.

The iterative process of design evaluation, modification, and optimization is not merely about achieving functionality but also about refining the design to enhance performance while reducing costs and material use [16]. By employing CAE tools, engineers can simulate and adjust various parameters dynamically, thus accelerating the design process and increasing the reliability of the final product.

3.3. Integration of Non-Linear Modeling Techniques

An essential aspect of this CAE-based approach is the incorporation of non-linear modeling techniques to accurately simulate the real-world behavior of gasket and seal materials under stress. These models take into account the non-linear elastic properties of the materials used, as well as the potential for non-linear deformation under load. For instance, using non-linear spring-gap element models, engineers can predict how gaskets and seals will perform under compression and tension, providing a more accurate depiction of their behavior during assembly and operation.

Moreover, this modeling approach allows for the adjustment of material properties based on the observed performance, integrating data from real-world tests and simulations to continuously refine the material models used. This holistic approach ensures that the gaskets and seals are not only designed to meet theoretical expectations but are also proven to perform under practical conditions.

The CAE approach to gasket and seal design is a comprehensive process that integrates advanced simulation techniques with iterative design improvements. By thoroughly evaluating every aspect of the seal's performance within the assembly, engineers can ensure that the final product not only meets the required specifications but also contributes to the overall reliability and efficiency of the machinery it supports. This methodical approach is essential in industries where precision and durability are paramount, such as in automotive and aerospace engineering.

IV. DATA-DRIVEN SEAL CAE PROCESS

Overview: The "Data Driven - SEAL CAE Process" outlines a robust framework for automating and optimizing simulation processes in engineering, particularly focusing on sealing applications within automotive and aerospace industries. The process leverages various scripting and automation techniques to streamline the creation of simulation models, execution of analysis variants, and management of output data. Table 7. Explains the process and steps of Data driven CAE.

The "Data Driven - SEAL CAE Process" represents a sophisticated integration of CAE technologies with advanced scripting and data analysis techniques. By automating routine tasks and systematizing the analysis of variant simulations, engineers can focus on optimizing designs and exploring new innovations in seal engineering.

This approach not only enhances the efficiency and accuracy of simulations but also aligns closely with modern industry practices that emphasize data-driven decision-making and automation in engineering workflows [16].

4.1. Variant Details in SEAL CAE Process

The SEAL CAE process involves the creation of various variants to thoroughly test the seal designs under different conditions. Here's how these variants are typically structured:

- **Part Variants:** Different geometrical configurations of the seal are created to assess fit, durability, and performance under dynamic conditions. For instance, Part-1 might have 3 variants, each with slight modifications in cross-sectional design, while Part-2 might have 5 variants focusing on length and flexibility adjustments.



Fig.9. Outer Part variant detail

- **2D - Mesh variant:**

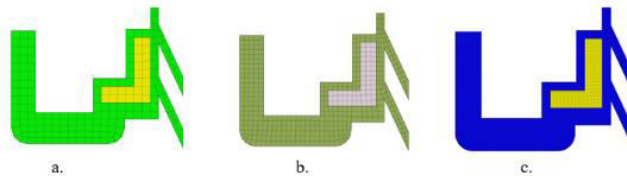


Fig.10. Mesh sizes, a.0.5mm, b.0.3mm, c.0.1mm

- **Material Variants:** Various materials are tested to understand their impact under different operational environments. For example, three different elastomeric materials could be tested for their reaction to temperature variations and mechanical stress [16].
- **Coefficient of Friction Variants:** These variants are crucial for understanding how different surface treatments affect the seal performance in terms of friction, which can significantly impact wear and sealing efficiency. Typically, six different coefficients are tested ranging from low to high friction values.

Table.9. Variant combinations

Component	Variants	Total Combinations per Component
Mesh Type	3	$5 \times 3 \times 4 \times 6 = 360$
Outer Diameter	5	
Materials	4	
Coefficient of Friction	6	

4.2. Process-1_Semi-automatic

- Initially, the basic model run file is prepared manually. Subsequently, a custom-made Python script automates the preparation of the remaining 359 variant run files.
- The script also generates batch files for each run file along with a master batch file to manage the batch processing.

- It automatically generates images in a specified format and integrates these visuals into PowerPoint presentations for easy review and presentation.
- The script extracts XY data from each result file, consolidating this data into a single file for streamlined analysis.
- It creates plots for various scenarios across all variants, allowing for a comprehensive visualization of different design performances.
- This Python-script-based automation facilitates the customization of design variables, enabling the identification of optimal designs tailored to specific requirements.

This process significantly enhances efficiency by automating repetitive tasks and enabling detailed analysis and visualization of model outcomes, thereby supporting informed decision-making in design optimization.

4.3. Process-2_Parametric Optimization of Seals

Significant progress has been made in optimizing the sealing performance of seals in recent years, with most research focusing on design aspects. For instance, Wagner et al. proposed a foundational framework for seal design, addressing key factors such as compression force-displacement behavior, deformed shapes during compression, contact pressure distributions, and differential pressures [17]. Similarly, Zhu et al. advanced design optimization by evaluating sealing properties, bending, twisting, and load distribution, employing door seals with various cross-sectional geometries [18]. Parallel research on rubber friction has taken diverse approaches. Tiwari et al. explored the effects of surface energy and contamination films on rubber friction, while Hale et al. highlighted the significant influence of rubber geometry on friction in relation to the sliding direction [19]. Additional investigations have examined stress concentrations at the leading edges of viscoelastic materials [20, 21].

However, a noticeable research gap remains in understanding the impact of friction on the deformed shapes and load distributions of seals during compression. Addressing this gap, the present study explores innovative approaches and supplementary factors to enhance the performance and durability of rubber seals in automotive applications.

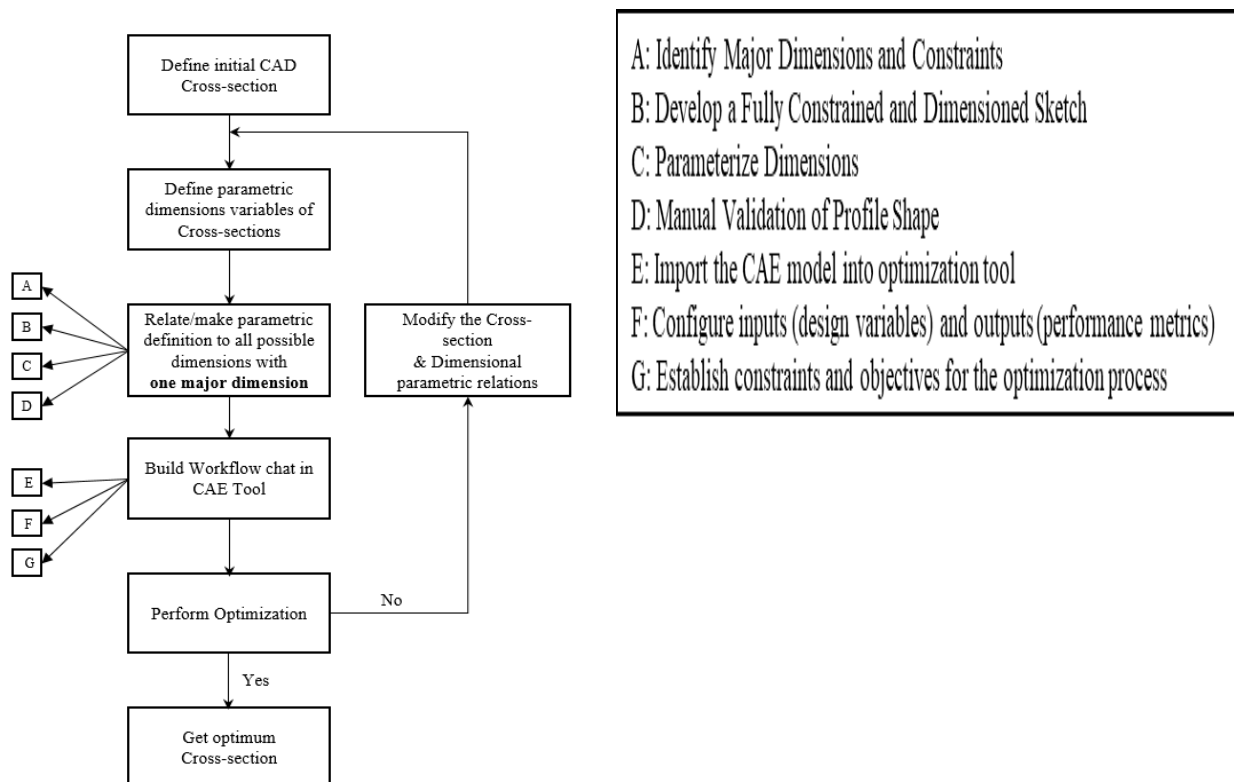


Fig.11. Multi-Variant Optimization process

By focusing on these dynamics, this study aims to contribute to the development of more efficient, durable, and high-performing rubber seals for modern automotive applications.

To achieve this objective, a simple yet representative omega seal was selected as the focal point of the investigation. Although various complex rubber seals are employed at structural interfaces, the omega seal offers a simplified model ideal for experimental analysis. This approach facilitates a comprehensive examination of the intricate dynamics between surface conditions, frictional forces, and sealing performance.

The FEA Sketch Parametric Manager is an advanced tool within the CAE tool environment, designed to streamline the creation and management of parametric sketches for finite element modeling. By allowing users to define and modify geometric features using parameters—expressed as mathematical equations or variables—it enhances flexibility, efficiency, and precision, particularly in iterative design processes and optimization studies. Refer Fig explains the traditional and multi-variant optimization process to identify the key design variable of seal performance.

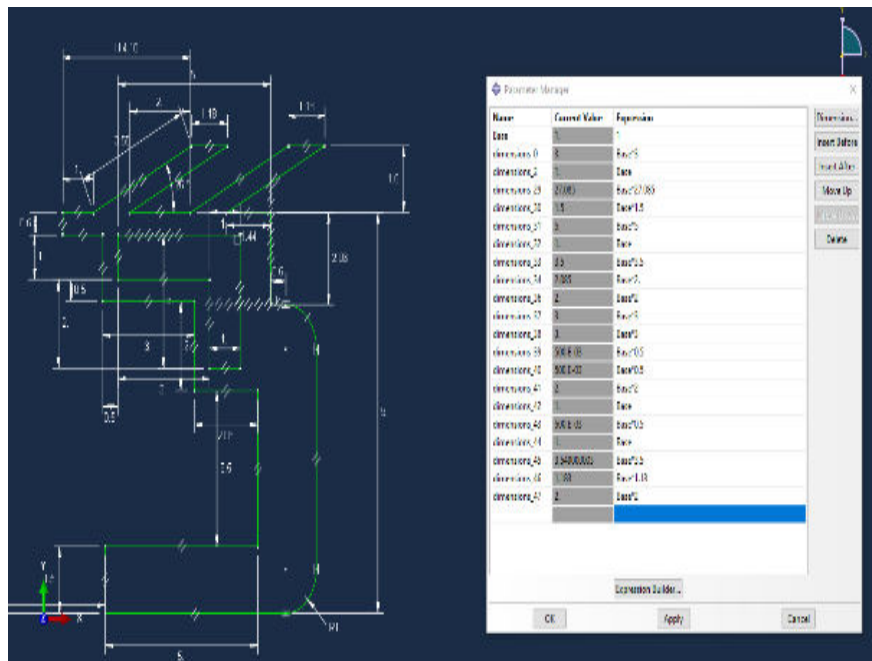


Fig.12. Multi-Variant Optimization process – Constrained sketch parameter

Refer Table 9. about multi-variant optimization process and Key steps in utilizing this tool for seal design.

V. RESULTS AND DISCUSSION

5.1. Results

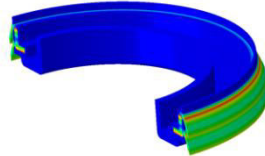
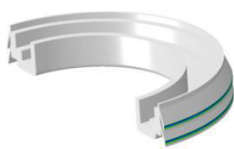


Fig. 13. a. Contact Status, b. Stress

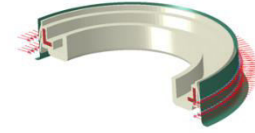


Fig. 14. Normal Stress vector plot

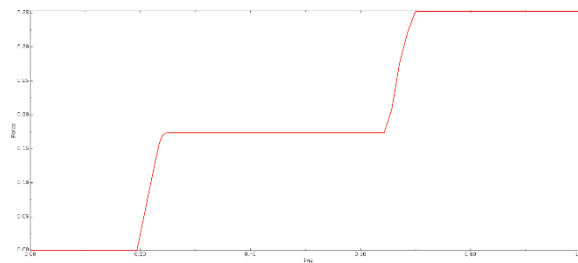


Fig.15. Outer Sleeve assembly Reaction force plot

Table.10. Variant combinations

	OD	CoF	Material	Model/ Mesh
Graph-1	all	0.5	NR60	0.1
Graph-2	28.5	0.5	all	0.1
Graph-3	28.5	all	NR60	0.1
Graph-4	28.5	0.5	NR60	all
Graph-5	28.5	all	all	0.1
Graph-6	all	0.5	all	0.1
Graph-7	28.5	0.5	all	all

5.2. Summary

Here's a refined and expanded summary of the analysis based on the Figures 16~29 referenced:

Outer Sleeve Diameter Impact: As shown in Figure: 18, reducing the diameter of the Outer Sleeve increases the assembly force, resulting in enhanced sealing force.

Normal Force Dependency on Sleeve Diameter: Referencing Figure: 23 again, it is observed that a smaller diameter of the Outer Sleeve leads to higher normal forces, which contributes to improved sealing effectiveness.

Material Hardness Influence: According to Figure: 19, increased material hardness raises the assembly force, which directly enhances the sealing force.

Normal Force and Material Hardness: Figure: 24 illustrates that greater material hardness also increases the normal force during assembly, boosting the sealing force further.

Coefficient of Friction (CoF) Considerations: As per Figures: 18 and 25, both assembly and normal forces increase with a higher CoF, though the impact is less significant compared to changes in material or outer diameter. It's crucial to understand CoF under wet conditions, where sealing forces can vary due to slippery conditions.

Mesh Size Variability: Figures: 19 and 26 highlight differences in assembly and normal forces due to varying mesh sizes. While trends remain consistent, actual values differ and should be evaluated based on CAE expertise, past studies, or experimental data.

Material and CoF Interaction: Figure: 20 and 27 displays plots that combine material properties and CoF, showing their joint effect on assembly and normal forces.

Material and Outer Diameter (OD) Sleeve Variants: Figure: 21 and 28 shows how variations in material and the OD of the sleeve influence both assembly and normal forces.

Material and Mesh Size Variants: Figure: 22 and 29 demonstrates the effect of different mesh sizes combined with material variations on the forces involved.

These plots provide a clear visualization of how different design variables influence the sealing performance, enabling the identification of optimal seal design variables for further development.

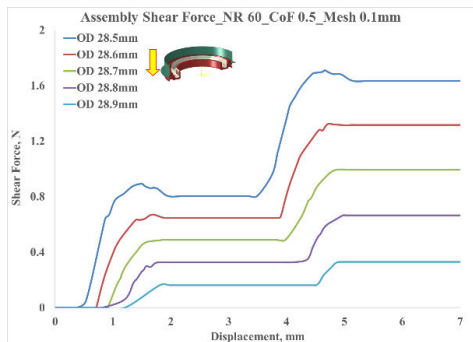


Fig. 16. Reaction Force_OD variants

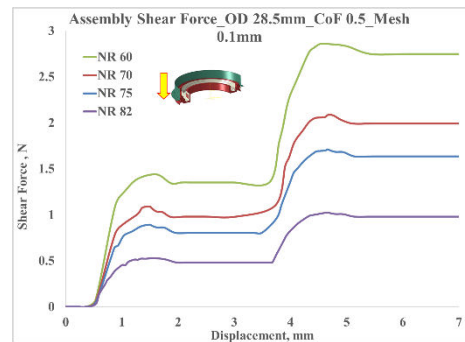


Fig. 17. Reaction Force_Material variants

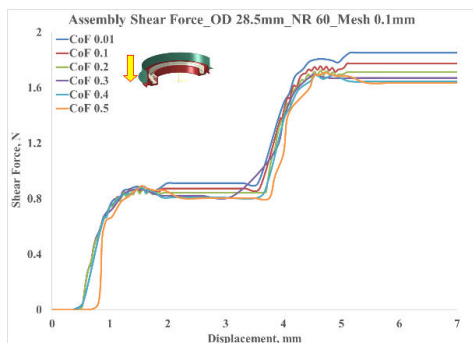


Fig. 18. Reaction Force_CoF variants

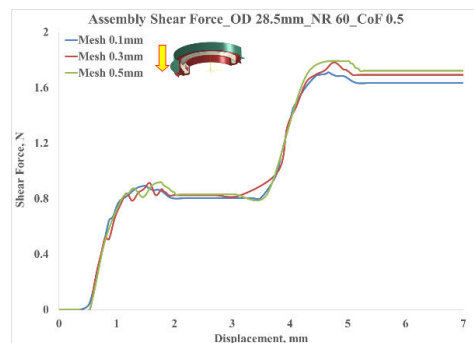


Fig. 19. Reaction Force_mesh size variants

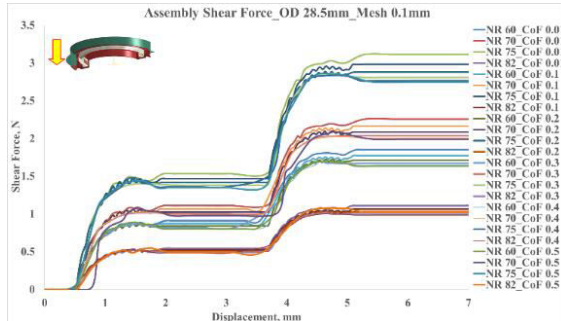


Fig. 20. Reaction Force_Material & CoF variants

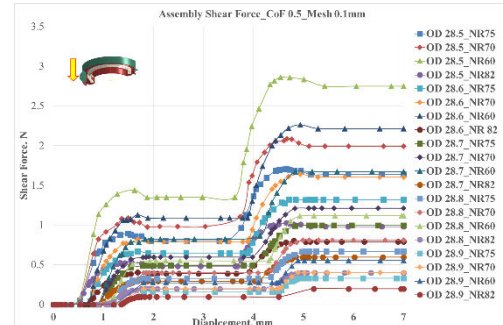


Fig. 21. Reaction Force_OD & Material variants

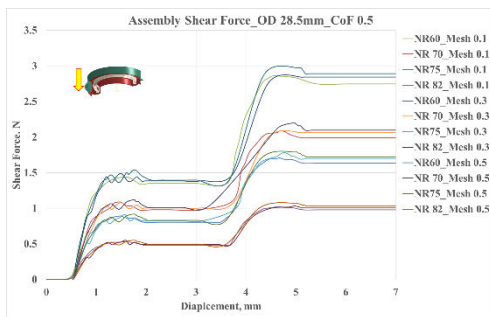


Fig. 22. Reaction Force_Material & Mesh size variants

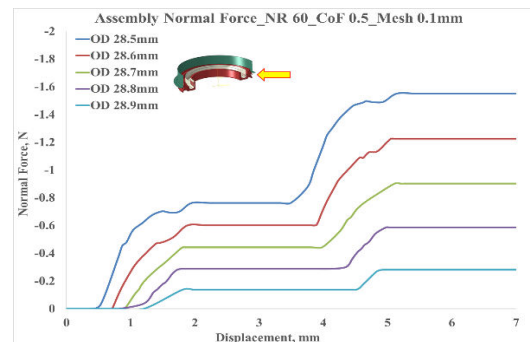


Fig. 23. Normal Force_OD variants

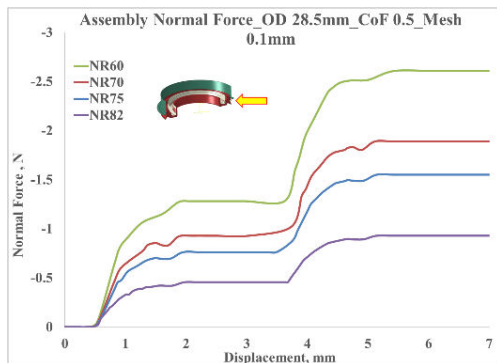


Fig. 24. Normal Force_Material variants

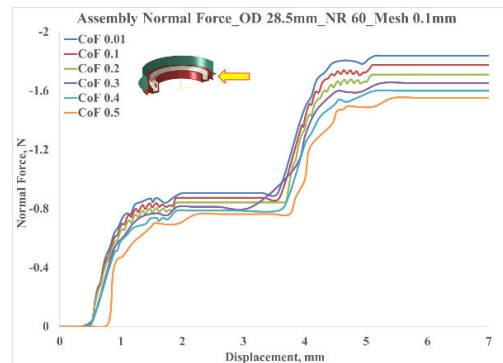


Fig. 25. Normal Force_CoF variants

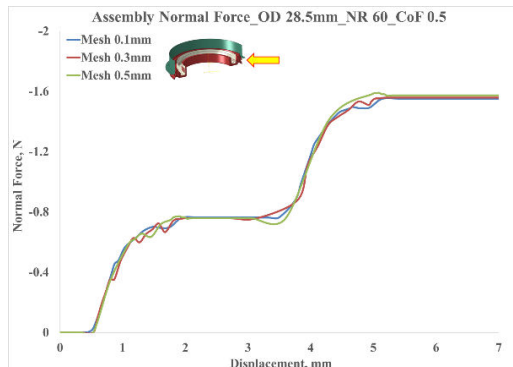


Fig. 26. Normal Force_Mesh size variants

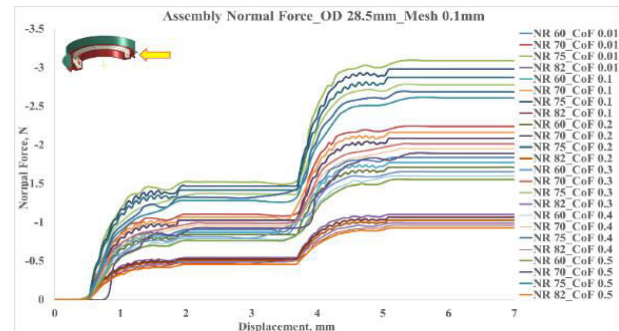


Fig. 27. Normal Force_OD & Material variants

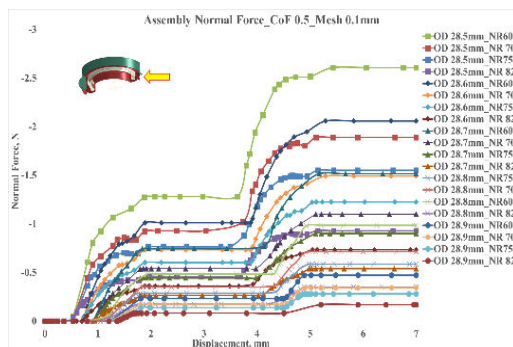


Fig. 28. Normal Force_OD & Material variants

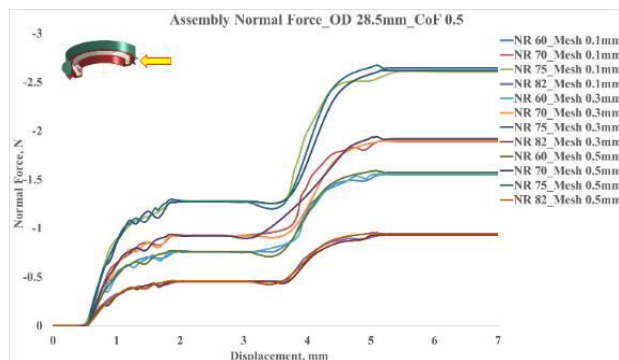


Fig. 29. Normal Force_Material & Mesh size variants

NOMENCLATURE

NVH	Noise, Vibration and Harness
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
FKM	Fluoroelastomer
FEM	Finite Element Model
CAD	Computer Aided Design
OD	Outer Diameter
PTFE	Polytetrafluoroethylene
CoF	Co-efficient of Friction

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APPENDIX

Table.1. Seal Types

Seal Type	Applications	Key Features	Benefits
Bearing Seal	Used in automotive bearings	Protects against contaminants, reduces friction	Enhances bearing life, improves performance
Body Seal	Doors, windows, other body components	Weather resistance, durability	Protects interior from elements, reduces noise
Driveline Seal	Transmissions, differentials	High-temperature resistance, fluid retention	Prevents leaks, extends component life
eDrive Unit Seal	Electric motor units, hybrid vehicles	Electromagnetic interference shielding, durability	Supports EV performance, protects against failures
Engine Seal	Engine components like valves, pistons	Heat resistance, chemical resistance	Prevents engine leaks, maintains engine efficiency
Suspension Seal	Suspension assemblies	Abrasion resistance, environmental resistance	Ensures smooth ride, protects suspension parts
Wheel End Seal	Wheel bearings and hubs	Grease retention, contaminant exclusion	Extends wheel life, reduces maintenance needs

Table.2. Typical Design Concerns in Gasket/Seal Engineering

Concern	Description
Seal ability of the Joint	Ensures a leak-free interface between joined surfaces. Requires selecting suitable materials and designing to match mating surfaces accurately.
Material Failure Upon Assembly	Materials must withstand compressive loads from bolts or clamps without failing, to maintain integrity from initial assembly.
Flange Failure Under Excessive Clamp Loads	Flanges should resist deformation, cracking, or permanent set under high clamping forces, necessitating robust material and design analysis.
Long-Term Performance and Creep	Materials should endure environmental aging and stress without significant degradation in clamping force or seal integrity.
Thermal Distortion	Design must accommodate the thermal expansion or contraction of materials, which may otherwise lead to seal failure.
Addressing Non-linear Behavior and Creep	Advanced CAE simulations are required to model non-linear material behaviors and interactions under dynamic conditions.

Table.3. Typical Design Variable Concerns in Gasket/Seal NVH & Tribology

Property	Aspect	Impact on NVH Characteristics	Impact on Tribological Performance
Coefficient of Friction	Noise Reduction	Reduces noise from sliding contact	Increases wear rate, requiring frequent maintenance
	Vibration Damping	Dampens vibrations, reducing cabin noise	Ensures performance consistency over seal's life
Rubber Material (Shore Values)	Compliance	Provides compliance and flexibility, reducing noise	Affects durability, with softer materials deforming
	Seal Effectiveness	Harder materials may increase noise unless tailored	Softer rubbers better adapt to irregular surfaces

Table.4.Radial Seal – Characteristics

Criteria	Description
Material Resistance	Seal lip materials exhibit exceptional resistance to chemicals and high temperatures.
Pumping Efficiency	Exhibits a superior rate of pumping, enhancing performance.
Surface Imperfection Compensation	Special coatings on seals compensate for imperfections in the housing bore surfaces.
Design Robustness	Features a sturdy design for enhanced durability and reliability.
Standards Compliance	Adheres to both national and international regulatory standards, ensuring broad applicability.

Table.5. Radial Seal – applications.

Typical Applications	Description
Gearboxes	Utilized in gearboxes to maintain fluid integrity and prevent contamination.
Hydraulic Pumps	Essential in hydraulic pumps to ensure effective sealing under high pressure conditions.
Axles	Employed in axle systems to prevent leakage and protect against dirt and debris.
Power Steering Columns	Used in power steering systems to ensure smooth operation and prevent fluid escape.
Speed Reducers	Critical in speed reducers to maintain lubrication levels and system efficiency.
Transmissions	Applied in transmission systems to enhance performance by ensuring proper lubrication containment.

Table.6. Sealing Material

Rubber Type	Key Properties	Common Uses
Nitrile Butadiene Rubber (NBR)	Oil, fuel, and chemical resistance	Seals in automotive, oil & fuel handling
FKM (Fluoroelastomer)	Excellent heat, weathering, and chemical resistance	Seals in aerospace and automotive for high-temperature environments
EPDM (Ethylene Propylene Diene Monomer)	Excellent resistance to heat, ozone, weathering, and polar solvents	Outdoor applications, automotive weather sealing
HNBR (Hydrogenated NBR)	Good chemical resistance and better wear resistance than NBR	Automotive seals, oilfield exploration
Silicone Rubber	High thermal, weathering, and ozone resistance	Static seals, insulators in electronic applications
XNBR (Carboxylated NBR)	Increased wear resistance, maintains NBR properties	Heavy industrial applications, seals
Polyacrylate Elastomer	Heat resistance, resistance to ageing and ozone	Seals for automotive with EP additives, not suitable for water or dry running

Table.7. Work Flow step for CAE Driven process

Step Title	Description	Key Components
Simulation Setup	Initial setup of base simulation models in CAE software, defining essential simulation parameters for sealing applications.	- Geometric Parameters
		- Material Properties
		- Boundary Conditions
Generating Variants	Creation of multiple model variants using Python scripting to explore different design scenarios.	- Material Variants: Testing different materials for impact on seal performance.
		- Load and Boundary Conditions: Altering conditions to simulate operational environments.
Automation of INP File Creation	Employing scripts to automate the generation of .inp files from CAE models, enhancing efficiency and reducing errors.	- Python Script: Automates scanning of directories for .inp files and creation of .bat files for running Abaqus jobs.
Batch Processing and Job Management	Utilizing an overarching script to manage and execute multiple simulation jobs via a master .bat file.	- Master .bat File (ALL.bat): Runs all .bat files in a directory, optimizing job execution.
Data Collection and Analysis	Collecting and analyzing simulation data to provide insights into performance metrics and trends.	- Post-Processing Scripts: Compile simulation results for comprehensive data analysis.
Integration with Design Processes	Ensuring that simulation outputs are seamlessly integrated into broader engineering and design processes.	- Feedback Loops: Continuous integration of data into design decisions to inform and refine engineering outputs.

Table.8. Multi-variant Optimization process steps

Step	Description
1. Identify Major Dimensions and Constraints	Determine critical dimensions and constraints that define the weather-strip seal profile. Focus on key geometric parameters influencing performance characteristics such as compression load deflection (CLD) behavior.
2. Develop a Fully Constrained and Dimensioned Sketch	Create a sketch in the CAE tool's Sketch environment, ensuring it is fully constrained and accurately dimensioned. All geometric relationships and constraints should be clearly defined to prevent unintended shape changes during parameter adjustments.
3. Parameterize Dimensions	Use the CAE tool's Sketch Parametric Manager to integrate and parameterize dimensions. Establish interdependencies among dimensions to facilitate seamless adjustments during design iterations, maintaining geometric consistency and aligning with performance goals.
4. Manual Validation of Profile Shape	Manually check the profile shape at minimum and maximum values of major driving parameters. This ensures the profile remains within acceptable geometric limits while accommodating variations in design inputs.



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