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Research Article

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Fatigue Analysis and Design Optimization of Spacer Plates in Fuel Injectors under Variable Pressure Conditions

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Abstract This study investigates the fatigue failure behavior of the spacer plate in fuel injectors under fluctuating pressure conditions. Utilizing advanced CAD and Finite Element Analysis (FEA), a detailed 3D model of the fuel injector was developed to simulate realistic loading scenarios, including variable fuel pressures ranging from 180 MPa to 260 MPa and various mechanical loads. The analysis identified critical stress concentrations of up to 740 MPa near the fuel passage holes. Despite these high stresses, the Goodman diagram analysis confirmed that the spacer plate remains within safe fatigue limits under the applied conditions. The results highlight the spacer plate's structural integrity and robustness, offering valuable insights for improved design and material selection to enhance fuel injector durability and reliability.

Keywords Fatigue Analysis, Finite Element Analysis, Spacer Plate, Fuel Injector

1. Introduction

The spacer plate, a critical component in fuel injectors, is an essential interface between various mechanical elements, ensuring proper distribution of fuel pressure and alignment within the injector assembly. The structural integrity of the spacer plate is vital for the reliable operation of the injector, as it must endure significant mechanical stresses. Failure of this component can lead to catastrophic consequences, such as fuel leakage, reduced efficiency, and potential engine failure. Such failures compromise overall engine performance and safety, underscoring the importance of understanding and mitigating fatigue-induced failures in this component.

Despite the critical role of the spacer plate, existing studies have not explored the behavior of this component, particularly its fatigue behavior under variable pressure conditions. No research investigated static stress analysis or the influence of variable pressures that the spacer plate experiences during real-world engine operation. These limitations highlight the necessity for a comprehensive investigation into the fatigue failure behavior of the spacer plate under realistic loading scenarios.

The primary objective of this study is to bridge this gap by thoroughly examining the fatigue failure behavior of the spacer plate under variable pressure conditions. Using the Goodman diagram, the study will assess the spacer plate's fatigue resistance by computing the maximum principal stress distribution and analyzing the alternating and mean stresses.

The scope of this study extends beyond merely identifying stress distribution patterns. It aims to contribute to the broader understanding of fatigue failure mechanisms in fuel injector components. It offers valuable data to inform the design and material selection processes for enhanced durability and reliability. The relevance of this research lies in its potential to improve fuel injector performance, reduce maintenance costs, and enhance engine safety, addressing a critical need in the automotive and aerospace industries.

2. Literature Review

There is limited specific research directly addressing the spacer plate of fuel injectors. As an overall view, a literature review was written for different studies related to fuel injectors. Fuel injector nozzles play a crucial role in internal combustion engines, directly influencing fuel atomization, combustion efficiency, and emission levels. Recent studies have delved into various aspects of fuel injectors, including failure mechanisms, flow dynamics, manufacturing processes, and modifications for alternative fuels. Neto et al. (2015) [1] identified common failure modes in diesel engine fuel injector nozzles, such as wear, cavitation, and deposit formation, contributing to inefficient fuel delivery and increased emissions. Chen et al. (1993) [2] analyzed gasoline fuel injectors' dynamic and static flow characteristics, revealing the complex relationship between injector geometry and fuel spray formation. This work emphasized optimizing flow parameters for better fuel atomization and combustion efficiency.

Manufacturing processes and material considerations are also pivotal in the performance of fuel injectors. Hur et al. (2004) [3] conducted a finite element analysis (FEA) of the cold forging process used in manufacturing fuel injector housings. Their study provided insights into optimizing manufacturing parameters to reduce defects and improve structural integrity. Prasad (2017) [4] focused on the design evaluation and optimization of diesel engine fuel injector nozzles, highlighting the impact of nozzle geometry on spray characteristics and combustion efficiency. His research suggested design modifications that could enhance performance and reduce emissions. Scott-Emuakpor et al. (2017) [5] examines the application of the Constant Life

Criterion in predicting the fatigue behavior of turbine engine components. By utilizing the Goodman diagram, the study effectively correlates cyclic loading and mean stress to assess the endurance limits of these components. This approach enhances the ability to predict component lifespan and ensures reliable performance under varying stress conditions, thereby improving the overall design and durability of turbine engines.

Significant gaps remain in the literature, particularly concerning the spacer plate's fatigue behavior under variable pressure conditions. Existing research has predominantly focused on more straightforward components like nozzles and injector bodies, often neglecting the complex loading conditions that spacer plates experience.

3. Methodology

A detailed 3D model of the fuel injector was developed using advanced PRO/Engineer CAD modeling software (Fig. 1). The CAD model was exported to Altair Hypermesh as a STEP file for meshing.

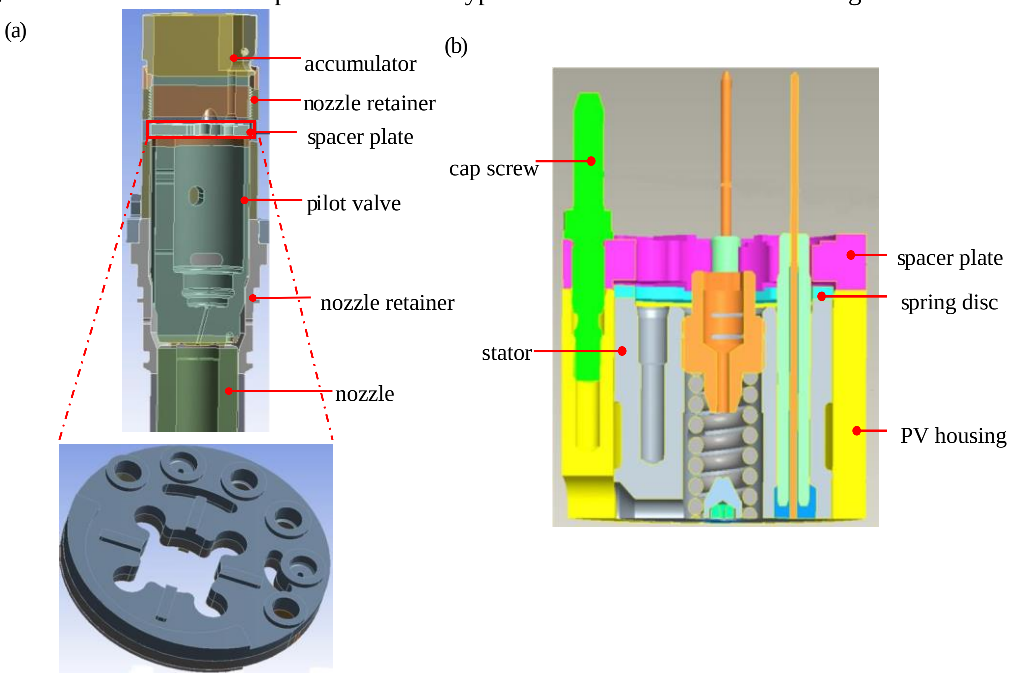

Figure 1: *CAD model of fuel injector (a) 3D model with enlarged spacer plate, and (b) sectional view of fuel injector*

The 3D model was discretized into finite elements. Four-nodded tetrahedral elements were generated to develop the finite element (FE) model. In all, 1,26,246 elements and 1,42,852 nodes were developed. The mesh density was optimized to balance computational efficiency and accuracy. Critical regions, such as areas with high-stress concentrations, were meshed with finer elements to capture detailed stress variations. The FE model was exported to the Ansys Mechanical 14.0 software package for assigning material properties, loading and boundary conditions, and FEA. All nodes at the base of the nozzle were constrained from moving in any direction (rotational and translational). Loading conditions were applied in eight steps. Initially, Load Step (LS) 1 applies a nozzle retainer torque of 56 kN along with a cap screw load of 5400 N on the spacer plate. LS 2, the conditions include the same retainer torque of 56 kN and an additional clamp load of 17.6 kN. LS 3 further incorporates a spring load of 2.9 kN to the existing 56 kN retainer torque and 17.6 kN clamp load. Subsequent load steps introduce variable fuel pressures: LS 4 combines the LS 3 conditions with a fuel pressure of 180 MPa, LS 5 increases this pressure to 200 MPa, LS 6 to 220 MPa, LS 7 to 240 MPa, and finally, LS 8 applies a maximum fuel pressure of 260 MPa along with the LS 3 mechanical loads. This progressive loading sequence analyzes the spacer plate's stress distribution and potential fatigue failure under various mechanical and pressure conditions. Young's modulus and Poisson's ratio were assigned to each FEA model component, as given in Table 1.

Table 1: Material properties of different components of the fuel injector

Component	Material used	Young's modulus (GPa)	Poisson's ratio
Nozzle retainer	SS4140	191	0.29
Nozzle	H13	191	0.29
PV housing	H13 50-55 HRC (hardened)	191	0.29
Spacer	SS4140	191	0.27
Accumulator	SS4140	191	0.29
Clamp adaptor	SS4140	191	0.29

The maximum principal stress distribution in the spacer plate was computed for each load step and reported for all load steps. Stresses at two sites were analyzed, and they were more susceptible to failure. The stress distribution was analyzed to identify critical stress points. The computed stress values were used to perform a fatigue analysis of the spacer plate. The alternating and mean stresses were determined, and the Goodman diagram was employed to evaluate the fatigue life of the spacer plate. The alternating stress was calculated as the difference between the maximum and minimum stress values during the variable pressure cycles. The mean stress was calculated as the average of the maximum and minimum stress values. Maximum principal stress and von Mises stress distributions were computed for all models. In all, four Goodman lines were plotted based on the material properties. The first line (red) denotes the boundary for a 50% failure probability to complete 10 million cycles. Then, a blue dotted line was plotted with a safety factor, including a 5% Coefficient of Variation (COV) for the ultimate tensile strength (UTS) and 8% COV for the fatigue strength. A third line (green) with further safety was developed considering a surface finish factor (0.838 Ra Derate Factor) and -3σ tensile yield line.

The Surface Finish Derate Goodman Line involves adjusting a material's fatigue strength to account for its surface finish's effects, using the Goodman line to incorporate mean stress impacts. Surface roughness, quantified by Ra values, can significantly influence fatigue performance, with rougher surfaces typically reducing fatigue strength due to the increased likelihood of crack initiation. A derating factor is applied to modify the fatigue strength according to the specified surface roughness in this context. For developing Goodman lines for the spacer plate, parameters are given in Table 2.

Table 2: Material properties considered to generate Goodman lines

Mean (temp derated)		COV	-3σ derate		Surface finish derate	
FS	450MPa	8%	FS	342MPa	FS	313.6MPa

UTS	1400MPa	5%	UTS	1190MPa	UTS	1190MPa
YS	1120MPa	7%	YS	884MPa	YS	884.8MPa

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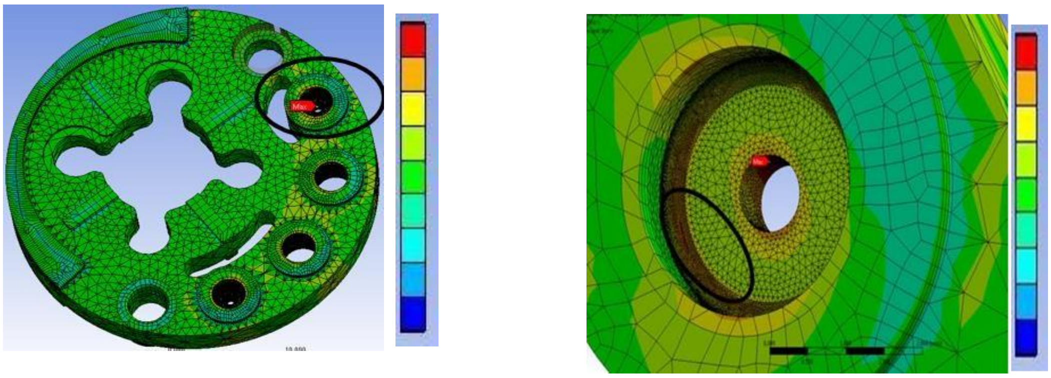
4. Results And Discussions

Figure 2 presents the first principal stress distribution in the spacer plate of a fuel injector, focusing on two specific locations around a hole where fuel passes through. Figure 2(a) showed the highest stress concentration of 740MPa at the location 1. Figure 2(b) showed a maximum stress of 660MPa at the location 2.

(a) (b)



740660
660602
491480
322323
153154 -15-13
-184-102
-353-350
-522-519
-691-687

Figure 2 *First principal stress distribution at spacer plate at location (a) 1 and (b) 2.*

Figure 3 shows (a) the Goodman diagram and (b) a detailed view of the spacer plate highlighting the two locations where fatigue analysis was conducted. Stresses of locations 1 and 2 (Figure 3(b)) were plotted on the Goodman diagram. Despite the high-stress concentrations near the hole, both locations were within safe limits, demonstrating the spacer plate's structural integrity under the applied loading conditions. Therefore, the design was robust under the specified loading conditions and not prone to fatigue failure.

(a) (b)

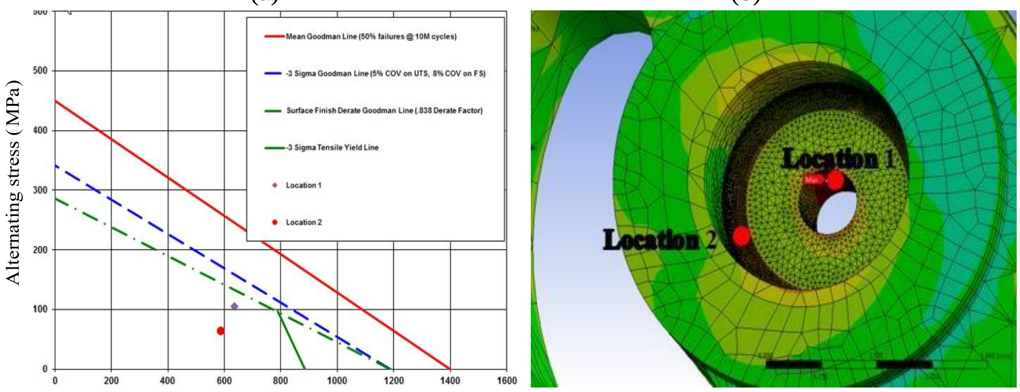


Figure 3 *(a) Goodman diagram of spacer plate and (b) locations at spacer plate where high stresses were recorded*

5. Conclusion

This study thoroughly examined the fatigue failure behavior of the spacer plate in fuel injectors under variable pressure conditions using Finite Element Analysis. The analysis revealed that the highest stress concentration was 740 MPa near a fuel passage hole. The Goodman diagram analysis showed that all critical locations remained within safe limits, indicating the spacer plate's structural integrity under realistic loading conditions. These findings have significant implications for improving spacer plate design, potentially leading to enhanced fuel injector durability, reduced maintenance costs, and increased engine safety. Future research could further explore the impact of thermal effects and different materials on the fatigue behavior of spacer plates.

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