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OPTIMUM DESIGN OF THERMO-PLUNGER SUPPORT IN COMMERCIAL VEHICLES BY USING STRUCTURAL DESIGN AND FINITE ELEMENT METHODS

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Abstract: This paper focuses on creating an optimum design and development of thermo-plunger parts for commercial vehicles in order to save material, reduce mass and make more sustainable automobiles. In this paper, natural frequency analysis, topology, and topography optimization methods have been used to create a new design for the thermo-plunger part. Thermo-plunger means an electric heater that is used for heating the inside of automobiles effectively and quickly and providing customer thermal comfort. It is positioned in the vehicle body, and its support parts have been developed by structural optimization techniques because there is not enough space in the engine compartment for automatic transmission commercial vehicles. The aim of this study is to make a lightweight and reinforced thermo-plunger support part design. Initially, a draft design was created in 3D model software. After that, topology and topography optimizations were applied on this draft design. At the end of studies, a final optimum support design has been obtained. The final design is 41.1% lighter than the initial design. At the same time, above 50 Hz natural frequency value has been obtained on the final design to avoid resonance problems.

Keywords: Optimum design, Topology optimization, Topography optimization

Yapısal Tasarım ve Sonlu Eleman Metodlarını Kullanarak Ticari Araçlardaki Termo-piston Destek Parçasının Optimum Tasarımı

Öz: Bu makale, malzemeden tasarruf etmek, kütleyi azaltmak ve daha sürdürülebilir otomobiller yapmak üzere ticari araçlar için optimum bir termo-piston parçası tasarımı ve geliştirilmesine odaklanmaktadır. Bu makalede, termo-piston parçasında yeni tasarım oluşturmak için doğal frekans analizi, topoloji ve topografya optimizasyon yöntemleri kullanılmıştır. Termo-piston, otomobillerin içini etkin ve hızlı bir şekilde ısıtmak için kullanılan ve müşteriye ısıl konfor sağlayan elektrikli ısıtıcı anlamına gelir. Bu parça araç gövdesinde konumlandırılmış olup, otomatik şanzımanlı ticari araçlar için motor bölmesinde yeterli alan olmadığı için destek parçaları yapısal optimizasyon teknikleri ile geliştirilmiştir. Bu çalışmanın amacı, hafif ve güçlendirilmiş bir termo-piston destek parçası tasarımı yapmaktır. İlk olarak 3B modelleme yazılımında taslak tasarım oluşturulmuştur. Daha sonra bu taslak tasarım üzerinde topoloji ve topografya optimizasyonları uygulanmıştır. Çalışmalar sonunda nihai bir optimum destek parça tasarımı elde edilmiştir. Nihai tasarım, ilk tasarıma göre %41.1 daha hafiftir. Aynı zamanda, rezonans sorununu önlemek için nihai tasarımda 50 Hz'in üzerinde doğal frekans değeri elde edilmiştir.

Anahtar Kelimeler: Optimum tasarım, Topoloji optimizasyonu, Topografya optimizasyonu

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1. INTRODUCTION

Lightweight, compact, and simple production designs with lowcost and highquality are very significant factors in meeting customer satisfaction, providing emission norms and surviving in a competitive arena for all automobile companies nowadays.

Most companies give importance to and allocate budget for their R&D activities to make innovative designs that have these characteristics. Also, it is possible to cooperate with universities and other companies in order to combine their knowledge and know-how (Yıldız et al., 2019). In addition, brands must design automotive components by taking advantage of developments in material technologies and software with new generation approaches. Optimization methods are the most useful approaches while designing a new part or developing a current part.

Optimization is a very important technique for the parts in vehicles to reduce material, costs, and weight. Different optimization methods are mentioned in the literature, such as topology, topography, shape, and size optimizations (Valverde et al., 2019). Each optimization method has a different purpose and usage.

Topology optimization is a useful method for conceptual design and helps to decrease the number of design cycles by minimizing trial-and-error iterations (Li et al., 2015). The aim of the topology optimization is to save raw materials and to provide mass reduction. It is one of the most effective structural optimization approaches and finite element methods (Zhuang et al., 2016). Applying this method to the first stage of the design, it can help build the design base effectively and produce the most suitable designs for the following and final design phases. Topology optimization is being extensively used in different sectors such as mechanical, automotive and aerospace, because it is an efficient and a highly developed tool (Sigmund, 2011).

Topology optimization is a helpful method to obtain more simple geometries on engine parts, moreover, it can be defined as an identification of optimal design. Optimal structural geometry is a sign of regular and uniform material distribution over the design domain (Torii et al., 2016). Thus, raw materials are used in the most efficient way. When there is limited space, topology can be used to produce new ideas and different design options as it allows to know where to add or remove materials, as well as the make better designs (Giechaskiel et al., 2019). Moreover, weight reduction by using this method affects the emission quantities. Road transport is the second most important source of air pollution in European Union countries (Biyikli and To, 2015). To regulate emissions, Euro norms are applied in these countries (Cavazzuti et al., 2010). In innovative technologies like hybrid vehicles, the topology optimization method is also preferred for fuel efficiency and lower emissions (Kong et al., 2016).

Due to all of its benefits, topology optimization has frequently been used to obtain better designs on many automobile parts. Since conventional trial and error design methodology is not enough to make automotive component designs, topology optimization is being used more and more nowadays in order to design light-weight and high performance components (Mantovani et al., 2017). As a result of topology optimization, the cost, the material quantity, and the weight will be minimized under various limitations such as stress, displacement and vibrations.

Topography optimization can be defined as a simulation method which reinforce parts without adding material and obtain optimal bead distribution that meet performance requirements (Shobeiri, 2016). Topography optimization is mostly applied on sheet metal parts. It is used to solve NVH problems and maximize the natural frequency of some vehicle parts (Kim et al., 2019). It is also a useful optimization method in order to make better designs on stamped sheet metal or molded plastic parts with minimum user input and automatic shape variable generation (Brennan and Hayes, 2000).

This method is concerned with the distribution of rib structures formed in order to increase the strength of the structure on sheet metal parts. These rib structures act as localized reinforcements (Costi et al., 2011). Therefore, topography optimization can be defined as an advanced form of shape optimization that allows shape changes based on ribs in a particular design region on the structure. The convex and concave shapes can be created on the sheet metal to increase the natural frequency and, as a result, to avoid resonance problems. The main aim of the topography optimization is to find optimum bead pattern in a vehicle component which has a shell form (Cavazzuti et al., 2012).

The topography optimization approach is very similar to the approach used in topology optimization, except that shape variables are used more often than density variables. The design region is divided into several variables whose effect on the structure is calculated and optimized by a series of iterations. It is used to find the optimum rib distribution on the structure within certain constraints. The advantage of the topography optimization compared to other methods, it needs minimal manufacturing effort and cost without additional increase in weight (Kim et al., 2019). As a short definition, this method increases the stiffness of component by modifying the geometry, especially the weak areas (Darge et al., 2014).

Thermal comfort in the vehicle cabin is very important to ensure customer satisfaction, especially for regions with cold climatic conditions. Electric heating technology is used to heat the vehicle cabin as quickly as possible, even in the harshest weather conditions. Thermo-plunger is an additional electric heating element that warms up the coolant that passes through the engine and then to the heater core that warms the passenger compartment. The main function of thermo-plunger is to make the passenger compartment a little warmer and de-froze the windshield during extreme cold weather conditions. During early mornings in extremely cold countries like Europe and Russia, the engine will take little time to send the required heat to this de-frozen and passenger heater and the thermo-plunger unit fulfils that job.

When a diesel engine is in idle condition, before moving the vehicle, the engine will produce few amounts of heat. In such cold conditions, this thermo-plunger will play a major role. Once the vehicle starts moving, and more heat is produced by the engine, the engine coolant will reach enough temperature to operate the heater and the thermo-plunger will switch off. Thermo-plunger will be present coolant circuit between heater outlet and engine inlet circuit, and it will be operated by an electric relay.

The automatic gearboxes provide a high driving comfort. But the most important disadvantage of the automatic gearbox is that they require a larger volume in the engine compartment compared to the manual gearbox. This situation necessitated the positioning of the thermo-plunger in a different region with alternative architectural works. Also, thermo-plunger and its support should be minimized by using optimization methods because of this reason.

In this paper, due to the change of place of thermo-plunger it is become compulsory to design new support. Topology and topography optimizations have been used to obtain lightweight, low cost and durable support parts which have the function of lifting and protecting thermo-plunger parts.

2. DESIGN AND OPTIMIZATION STUDIES

2.1. Design Studies

Because of the reasons mentioned in the previous section, for the current vehicle configuration, there is not enough space on the engine for the current electric heater and its support which are shown in Figure 1. The electric heater to be used in vehicles with automatic transmissions should be located within the engine compartment but not on the engine directly. Its support parts should be developed by structural optimization techniques.

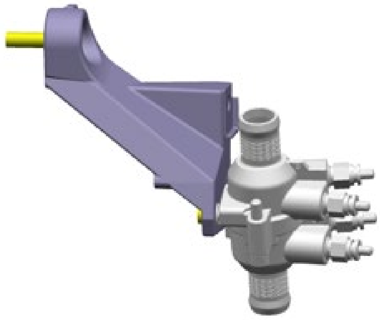


Figure 1:
Current design

Considering all the connection points, the distances of the bracket to the peripheral parts, oscillation of the parts, and safety rules, the most appropriate volume in the engine compartment was determined for the design of the electric heater support part.

The functional dimensions, tolerance ranges, and material properties of the electric heater and the support part are determined to perform their functions on the vehicle. Two holes have been introduced on the left fender support plate of the engine compartment in order to fix the support to the vehicle. This connection will be ensured with the bolts and nuts, as displayed in Figure 2.

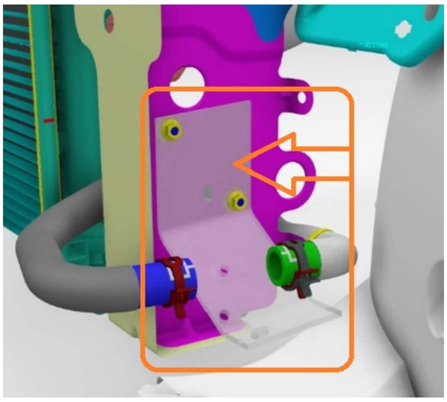


Figure 2:
Zoomed image of thermo-plunger, support and connections

The left fender support plate, in which the bracket of the thermo-plunger is in direct contact, must be provided with a clearance-free seating surface. This surface is referred to as reference A and is restricted by giving position tolerance.

The first connection is made between the pilot hole on the bracket and the left fender support plate to restrict the movement of the part in the Y direction. This hole is called as B reference. It is limited by perpendicularity tolerance and has the risk of axial misalignment, non-installation, and non-compliance with permanent torques if it does not meet the requirements.

In order to restrict the translation and rotation in the X, Y and Z directions, the part is secured through the second connecting hole on the bracket. This hole is defined as C reference. This hole is restricted by position tolerance. There is a risk of failure to mount and contact with surrounding parts if the conditions are not followed. All these three references (A, B and C) are shown in Figure 3.a.

Positioning of the electric heater on the support is done with bolts to be tightened on the bracket. The surface to which the bolts are tightened is referred to as the D reference (Figure 3.b). The seating surface of the two parts shall not exceed 13 mm in diameter. The purpose of this constraint is to ensure the full contact of the two parts. If there is a deflection in the inclination of the seating surface, the position of the electric heater in the space changes, and this affects the cable course. Therefore, it is limited to flatness tolerance.

Thermo-plunger will be positioned with the help of bolts on the bracket. Reference E (Figure 3.b) which is restricted the movement on the axis X, Y and Z and provides first positioning. The position tolerance is defined according to reference B, and measures are taken against the risks of axial misalignment of bolts on the bracket, mismatch in residual torques, and contact with surrounding parts.

The electric heater shall be positioned with the help of bolts tightened on the bracket. With the second bolt for final positioning, the electric heater will no longer be able to rotate.

The positioning of the cables on the bracket is carried out with the help of clip. The clip is attached to the hole on the bracket. This hole is called the F reference (Figure 3.b). No drift in hole position is desired.

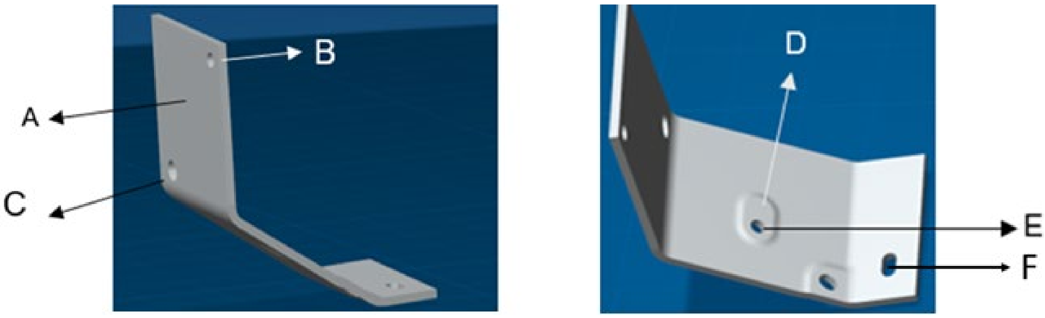
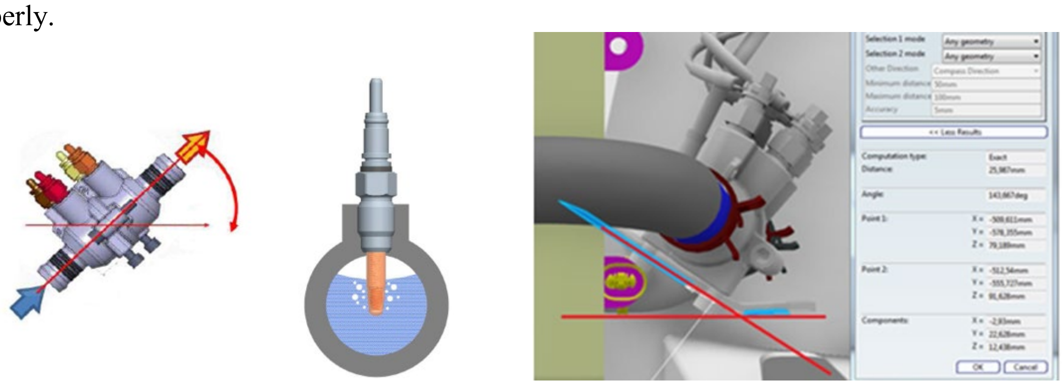


Figure 3:
a. *Reference A, B and C* ***b.*** *Reference D, E and F*

Misalignment in the position may result in the cables not being installed in the proper position. It is restricted to the position tolerance which is given according to references A, B and C.

The natural frequency target value was determined as 50 Hz. The position of the thermo-plunger in the vehicle is shown in Figure 4.a. By considering the position of the thermo-plunger, the inclination angle of the support was determined as a minimum of 45° with the horizontal surface, which is marked in Figure 4.b. This angle is preferred to perform support functions properly.



a. *b.*

Figure 4:
The position of the thermo-plunger in vehicle ***b.*** *The inclination angle of the support part*

2.2. Optimization Studies

For functional technical analysis of the electric heater support part, internationally valid norms, patents, publications, and applied examples in the market were examined. In the light of the data and information obtained, the functional dimensions, tolerance ranges, and material properties of the electric heater and the support part were determined. The relationships between the identified features and the surrounding parts were also examined. Considering the connection points determined as a result of functional technical analysis, considering the distances of the support part with the peripheral parts, oscillation of the parts, safety, and other rules, favorable volume in the engine compartment determined for the electric heater support part design. Determined design volume and connection points were drawn as a 3D model which is shown in Figure 5 with CATIA software. This model was defined as the initial design.

Figure 5:
Initial support design

As the first step of optimization of support, the topology optimization method was applied on initial design. Connection points were defined as non-changeable areas on the support. In addition, topology optimization was carried out by considering target and boundary conditions.

Figure 6 shows the output of the topology optimization on the bracket. While red areas represent the non-changeable areas, blue areas show the changeable areas which can be removed fully or partially.

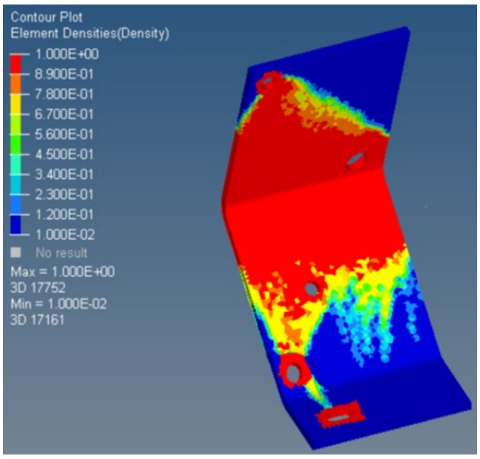


Figure 6:
Topology optimization of initial support design

Support was redesigned by taking the topology optimization output into consideration in Catia software. Figure 7.a shows the second support design. To provide more material savings and weight reduction, the third design, which will fulfill the functions fully like the previous ones, has been created on the support part, as shown in Figure 7.b, in Catia software.

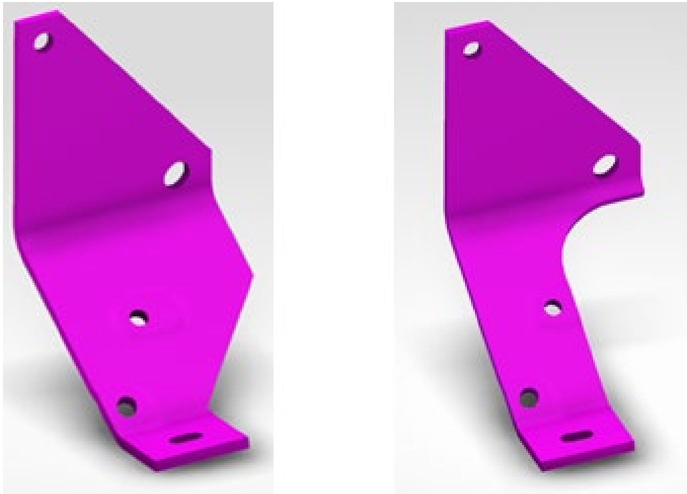


Figure 7:
a. *Second support design* ***b.*** *Third support design*

The second step of the optimization study is applying topography optimization on the third support which is obtained after topology optimizations. In the topography optimization by using HyperWorks software, OptiStruct module, the 3D model has been developed by taking into account the reproducibility/industrialization of the new geometry.

For topography optimization, some areas were defined as non-changeable areas. These are the connection points and the area where the electric heater is placed. Non-changeable areas were marked with red color, as shown in Figure 8.

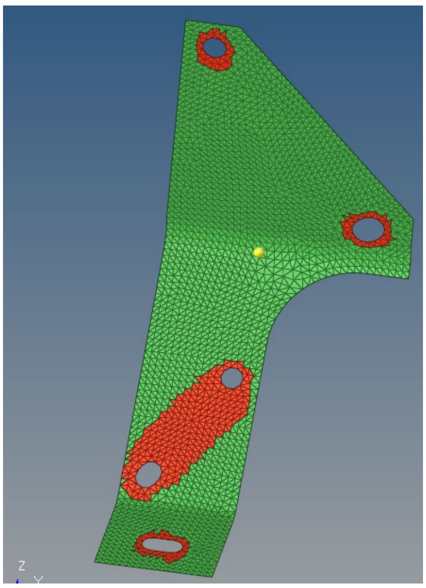


Figure 8:
Mesh structure and non-changeable zones

Furthermore, topography optimization was carried out by considering the target and boundary conditions. The topography optimization output is shown in Figure 9. In this figure, while blue areas mean that there will be no change required, red areas can be changed in the way of concave or convex by taking the geometric conformity into account.

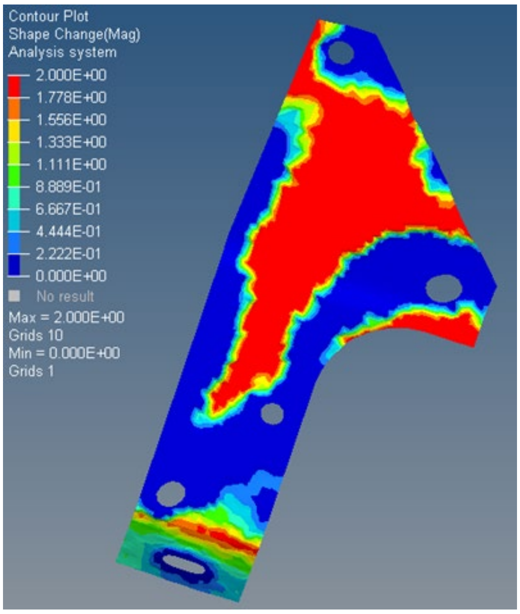


Figure 9:
Topography optimization output

The topography optimization output was transferred to the Catia software again, and the support design was renewed, as shown in Figure 10. This design can be defined as final design of the support part.

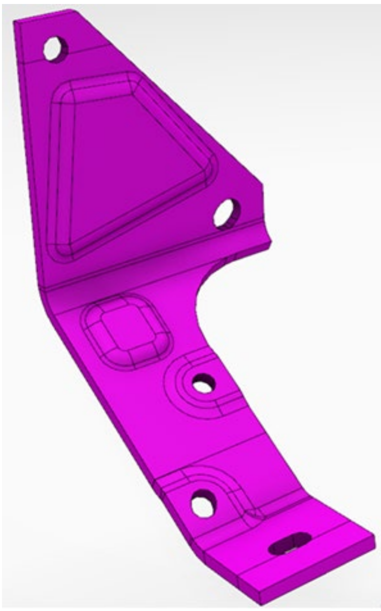


Figure 10:
Final design

3. CONCLUSION

The methodology of this study can be summarized as firstly creating an initial thermo-plunger support compatible with the space of the engine compartment and peripheral parts, secondly using the topology optimization in order to reduce the material quantity and weight of the part, and finally applying topography optimization to reinforce the part and increase natural frequency value of the part, respectively.

At the end of this study, an optimal support part has been obtained, and the targets have succeeded. The first target is to reduce the material quantity and weight of the support part. The weight of the support part decreased by 41.1% from the initial design to the final design phase, thanks to topology optimization. While the initial design mass is 0.428 kg, the final design mass is 0.252 kg.

For every design phase, natural frequency analysis has been realized to ensure the target value, as shown in Figure 11. The natural frequency value, was obtained as 170 Hz for the initial design, 182.3 Hz for the second design, 193.7 Hz for the third design, and 224.2 Hz for the final design. This is the second target determined by considering engine compartment vibration level to avoidany resonance case.

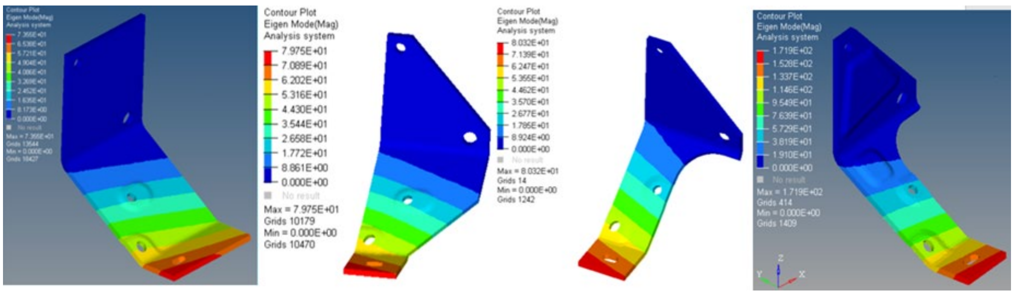


Figure 11:
Final design

For the following and advanced studies, the final design can be produced as a prototype part, and this part can be tested in vehicles in real road conditions. In this way, endurance, effectivity, and the performance of this part can be observed.

CONFLICT OF INTEREST

The authors confirm that there is not any conflict of interest or common interest with any institution/organization or person.

AUTHOR CONTRIBUTION

Ulaş Aytaç Kılıçarpa has created base of the study by making the literature research. Prof. Dr. Ali Rıza Yıldız and Doç. Dr. Betül Sultan Yıldız have performed the optimization and design studies. The results have been examined and evaluated by all of authors.

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