Article
Journal Industrial Engineering
December 2023, Vol.7 No.19 1-12

Topological and structural optimization of the brake pedal of a vehicle for the BAJA SAE 2023 competition

Optimización topológica y estructural del pedal de freno de un vehículo para la competencia BAJA SAE 2023

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DOI: 10.35429/JIE.2023.19.7.1.12 Received September 10, 2023; Accepted December 30, 2023

Abstract

The brake system is a critical area in the operation of a vehicle. To consider correct operation, various variables and components must be taken into account, including the brake pedal that activates the operation of the area. This study shows the conception of the design of the brake pedal of a BAJA SAE type vehicle and the optimization of its geometry using a methodology of analytical calculations with the essential variables of the system, taking into account SAE regulations for the competition, and subsequently through finite element analysis (FEA) and topological optimization methods using ANSYS software. Results of structural static studies, modal analysis and fatigue are presented for an initial model of the brake pedal and subsequently the topological optimization, presenting studies with similar conditions. The studies showed and structurally validated the optimized proposal of the pedal with a 30% reduction in mass and minimal variations in deformation and life cycles, as well as in behavior under vibrations. This pedal was manufactured and used in the BAJA SAE Mexico 2023 competition, showing adequate performance for its technical requirements.

BAJA SAE, Topology optimization, Fatigue, Modal, ANSYS

Resumen

El sistema de frenos es un área crítica en el funcionamiento de un vehículo. Para la consideración de la operación correcta se deben tomar en cuenta diversas variables y componentes, entre ellos el pedal del freno que acciona el funcionamiento del área. Este estudio muestra la concepción del diseño del pedal de freno de un vehículo tipo BAJA SAE y la optimización de la geometría del mismo empleando una metodología de cálculos analíticos con las variables esenciales del sistema, tomando en cuenta normatividades SAE para la competencia, y posteriormente mediante análisis por elementos finitos (FEA) y métodos de optimización topológica empleando el software ANSYS. Se presentan resultados de estudios tipo estático estructural, análisis modal y fatiga para un modelo inicial del pedal de freno y posteriormente la optimización topológica, presentando estudios con condiciones similares. Los estudios mostraron y validaron estructuralmente la propuesta optimizada del pedal con una reducción del 30% de masa y variaciones mínimas en deformación y ciclos de vida, así como en comportamiento bajo vibraciones. Este pedal se fabricó y se utilizó en la competencia BAJA SAE México 2023, mostrando un desempeño adecuado para los requerimientos técnicos del mismo.

BAJA SAE, Optimización topológica, Fatiga, Modal, ANSYS

Citation: CORDERO-GURIDI José de Jesús, ALVAREZ-SANTIAGO Jesús Daniel, MARTINEZ-DIAZ Ana Paola and HERNANDEZ-URBANO Cesar. Topological and structural optimization of the brake pedal of a vehicle for the BAJA SAE 2023 competition. Journal Industrial Engineering. 2023. 7-19: 1-12

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Introduction

The BAJA SAE competition is an automotive event where different universities in Mexico plan, design, build and fine-tune a vehicle with the particular characteristics of an off-road car. In the 70s, the SAE organization (Society of Automotive Engineers) created an international competition for higher education students called Baja SAE where it was required to conceptualize and materialize a car capable of traveling on rugged terrain for leisure purposes. There are dynamic and design evaluations during the contest [1]. Figure 1 shows an image of the vehicle in competition.

Figure 1. BAJA SAE type vehicle

In the BAJA SAE competition, teams traditionally manage the vehicle in different systems, in order to adequately address the logistics, design and manufacturing of its different components. These systems are: vehicle structure, steering, drivetrain, suspension and brakes.

Braking is a critical system in the vehicle, a mandatory element and a test in the competition that validates the safe operation of the car. According to BAJA SAE competition regulations, the car must be equipped with a hydraulic brake system that acts on all wheels and is operated by a single pedal. The pedal is rigidly connected to directly push the brake master cylinder; The braking system must be able to lock all four wheels at static and road and unpaved speeds [2].

Within the components of the braking area, the pedal has specific operating requirements for its operation by regulation and by essential functioning of the system, which when met have been subject to optimization to have a light and resistant component that fulfills the function of braking, but seeking to add the least amount of mass to the final vehicle. Various authors have developed similar studies to optimize the braking system in BAJA SAE competition, Wang et al. [2] developed a simulation and evaluation of the behavior of the brake pedal for the BAJA SAE competition in China, evaluating different materials and geometric changes in the joints with the vehicle structure, seeking to optimize optimal structural results within the design range original. Correa-Arciniegas et al. [3] developed an optimization through design tools such as QFD and later the analysis of fluid flow in the brake disc, although the results were maintained in forces and pressures in the system by analytical calculation.

Regarding the brake pedal, Asanov [4] developed the study of the proposal for a brake pedal for a general vehicle, considering structural evaluations and deformations under the loads proposed in his study. On the other hand, Gupta et al. [5] developed the study and analysis of a brake system for the Formula SAE competition, with a methodology for calculating essential properties of the brake system, material selection, CAD modeling and finally finite element simulations. The optimization of the pedal was based on the definition of the pedal radius through iterations with MATLAB and analysis with various materials. Additionally, other components of the brake system were evaluated looking for mass reduction in the complete system.

Regarding topological optimization, Romero & Queipo [6] sought the optimization of brake pedal mass through a numerical model using variables related to structural analysis in the pedal of a Formula SAE vehicle, reporting as a conclusion an application of a design of experiments for the optimization of the variables and the corresponding pedal geometry. Finally, Sudin et al. [7] showed a study on a brake pedal of a conventional vehicle, with the application of the Altair Optistruct software to define optimization objectives and the corresponding comparison of the original model and its structural behavior, against the model with mass reduction.

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Method Description

For the development of the braking system for BAJA SAE 2023, the requirements and standards indicated for the 2023 competition were taken into consideration.

Regarding applicable standards with respect to Baja SAE competition, there are the following:

– J1703 - Motor Vehicle Brake Fluid - Standard: Establishes the standards for brake fluids that are used in motor vehicles [8].

– J429 - Mechanical and Material Requirements for Externally Threaded Fasteners - Standard: Establishes the mechanical and material requirements for externally threaded fasteners, such as bolts and screws [9].

Likewise, the Baja SAE regulation [10] mentions two requirements with which the braking system must comply, these requirements talk about materials, forces and function of the object of study (brake pedal), these sections of the regulation are:

B.7.1 - Brake system

The vehicle must have a hydraulically actuated primary friction braking system that acts on all wheels and is operated with a single pedal. The pedal must directly actuate the master cylinder via a rigid link (i.e. no cables allowed). The brake system must be capable of locking and sliding all wheels, both in static condition and at high speed, regardless of surface conditions or transmission mode. The braking system will have sufficient force to keep the vehicle at idle or at low part throttle. Brake pedals and associated components shall be constructed of steel or aluminum and shall be designed to withstand a minimum brake pedal force of 450 lbf (2000 N) [10].

B.7.1.1 - Independent Circuits

The braking system must be segregated into at least two (2) independent hydraulic circuits so that, in the event of a leak or failure at any point in one system, effective braking power is maintained on at least two wheels.

The development of this work was contemplated in 7 steps; which can be seen in the following diagram in figure 2. The first step is the collection of information from past competitions, later we continued with the calculations of the braking forces, once these variables were obtained, we continued with the analysis of the technical requirements, as well as the investigation and selection of materials, with the information obtained, the CAD modeling of the components and the numerical analysis were carried out and, finally, we present results that we obtained from both analyzes and the conclusions.

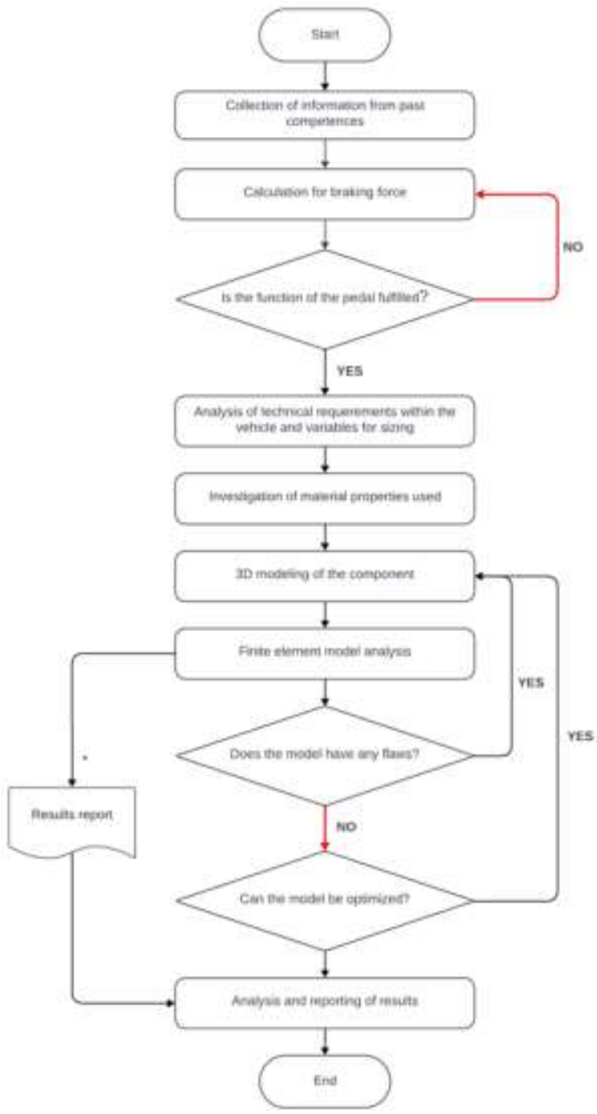

Figure 2. Method used for optimization

Analytical Approach to the Problem

Within the numerical evaluations, and for greater mastery in the development of the brake pedal, various fundamental equations of mechanics and statics for Baja SAE type vehicles were investigated, which are presented below:

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Pedal operation

The pedal is the control element of the braking system of a vehicle, which is why great attention must be paid when considering the principle of operation, design of the mechanism and its geometries. The braking force of the system will be proportional to the force exerted on the pedal, this is because the mechanism will function as a lever that transmits the force that comes from the foot to the hydraulic pumps.

In order to obtain a multiplier effect on the braking force, it is necessary that the distance between the axis of rotation to the actuator of the master cylinders be less than the distance from the axis of rotation to the area where the pedal is operated by the foot. By dividing both values, a value known as ratio will be obtained, which represents the relationship between the input force and the multiplication of the force that goes out to the master cylinder. The brake pedal has 2 different configurations; figure 3 shows a representation of each one along with the variables for calculating the pedal ratio.

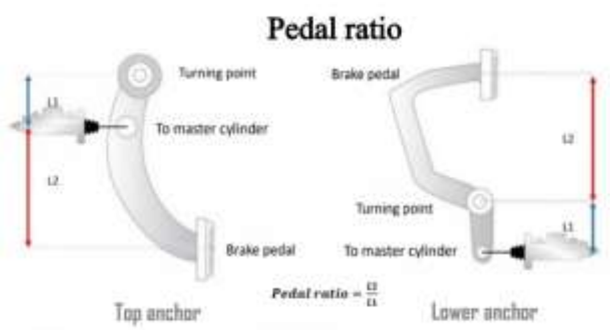

Figure 3 Types of brake pedal anchoring [11]

The pedal ratio is a very important factor which is calculated based on variables such as diameter of the master cylinders, diameter of pipes, type of brake system, etc. where the brake ratio can vary between 4 and 6.

There are 2 types of brake pedal mechanism:

– Pedals with top anchorage: the pivot point is located near the steering column in the area that separates the cabin from the engine,

– Pedals with lower anchorage: fixed to the vehicle floor so the pivot point is more coupled to the natural movement of the heel.

Braking forces

Braking is a common action while driving a vehicle, the objective of this action is to reduce the speed of the vehicle through the contact of 2 pads on a disc which rotates at the same speed as the tires, this through a hydraulic system which is activated by means of the brake pedal.

A hydraulic braking system bases its operation on the transformation of a force exerted on the brake pedal into a pressure on a fluid by means of a pump (in the case of the system the function is performed by the master cylinders), this pressure goes to move the cylinders of the brake calipers in such a way that friction is generated between the disc and the brake pad.

The principle of operation of the transmission of the force of a pedal is through a lever, like the one shown in figure 4, a lever is a simple machine which can transmit force or displacement, in this application it is used for the increase of a mechanical force, the objects of interest for the analysis of pedal force are:

– Applied force
– Resistance force
– Support point

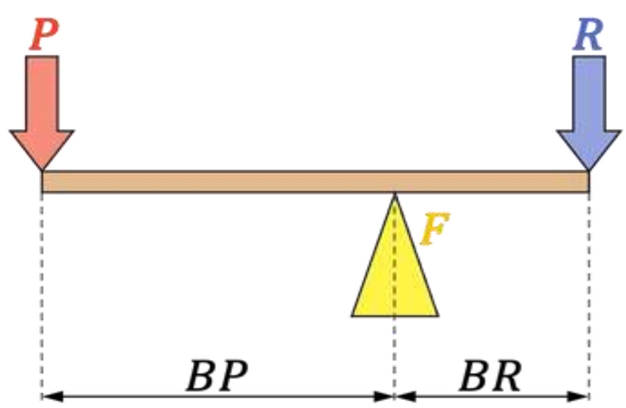

Figure 4 Representation of the variables of a lever[12].

The following equation presents a system in equilibrium of a plate.

$$F \times B_P = R \times B_R$$

Figure 5 Equilibrium equation of a lever

Where:

F= Foot force applied to the pedal
Bp= Distance from the application of force to the support point
R = Braking force transmitted by the pedal
Br= Distance from the support point to the force transmitted to the brake master cylinder

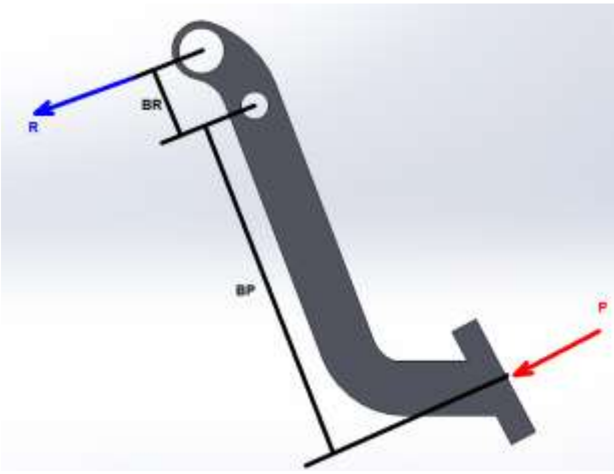

Figure 6 Lever representation in 3D model

Through the equation presented it will be possible to calculate the force transmitted by the pedal, which serves as input for the calculation of the braking force in the entire system.

Technical Characterization

For the Baja SAE 2023 competition, a disc brake system with calipers on all four wheels was chosen. Figure 7 shows a general diagram of the brake system.

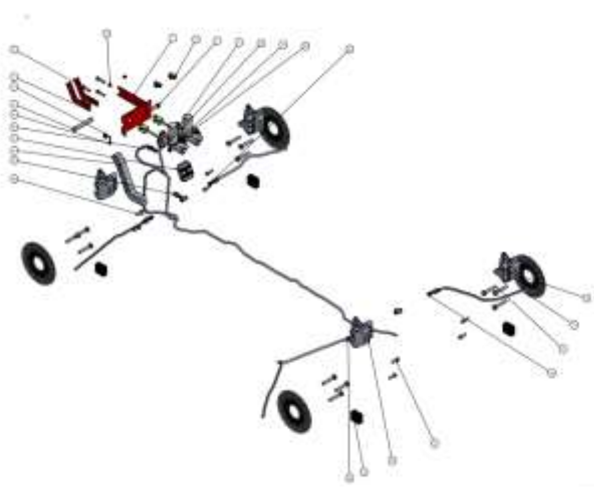

Figure 7 Exploded brake system

In this way, it can be established in an introductory manner that the braking system had the following elements described in table 1:

Ítem	Component	Amount
TIRE ZONE	Left caliper	2
	Right caliper	2
	Brake pad	8
	Brake disc	4
	Mass-disc fixing screws	12
	Caliper-knuckle fixing scew	8
FRONT PART	Master cylinders	2
	Brake post	1
	Brake footrest	1
	Cylinder connection bolt	1
	Pivot screw	1
	Nut for pivot screw	1
	Pedal union screw	1
	Cylinder-bolt union screw	2
	Nut for cylinder-bolt union	2
	Cylinder fixing screw	4
	Cylinder fastening screw nut	4
HYDRAULIC LINE	T hydraulic line	4
	Hydraulic system hoses	7
	Line-caliper union screw	4
	Hydraulic system adapter	2

Table 1. Brake system BOM

Regarding the components related to the pedal, Figure 8 shows a CAD model with the two independent brake pumps mounted on the brake pedal assembly.

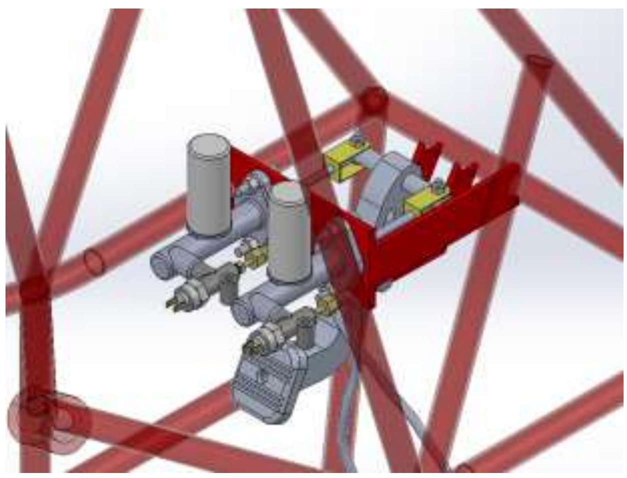

Figure 8 CAD model of pedal assembly with hydraulic pumps

Numerical Analysis

For the development of the CAD assembly of the pedal, shown in figure 9, certain requirements were taken into account, which were described in the regulations of the BAJA SAE 2023 competition.

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The main consideration that was mentioned in the regulations is that the pedal the brake must withstand a force of at least 2000 N and must be manufactured in steel with a minimum of 20% carbon concentration or 6061 aluminum, in addition to the requirements of the regulations for the competition, the design and modeling of the pedal was limited by variables both in the calculation of the force necessary to brake the vehicle, which influenced the distance from the support point and the area of contact of the foot with the pedal as well as the angle of inclination that would be between the area of the lever of the pedal and the foot support surface.

Figure 9 First CAD model of the pedal

Another issue which was of great relevance for the design of the pedal was the environment by which it was going to be surrounded, the first element that restricts the dimensions of the pedal was the chassis (made up of a tubular structure) of the vehicle and the position in the which the brake pump fastenings were positioned, having to take into consideration ergonomic elements due to the driver's driving position in such a way that the brake pedal will be in a position and have the appropriate geometry for the pilot to perform the action of pressing the pedal comfortably and that the pedal will perform its function, the result of these considerations are shown in figure 10 where the dimensions of the pedal are shown.

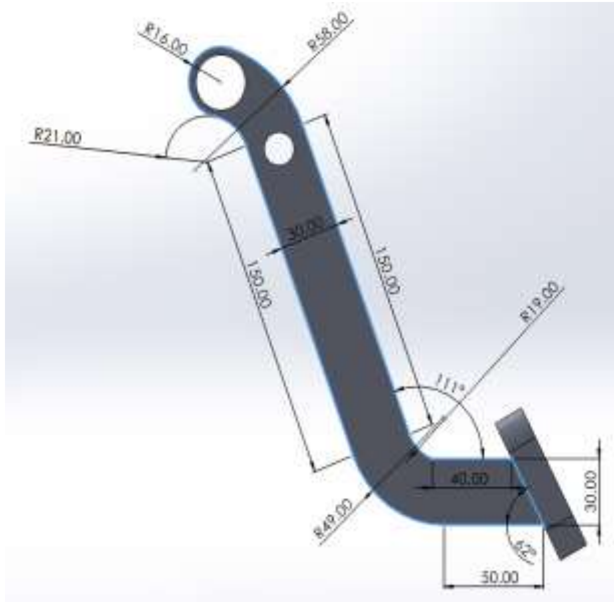

Figure 10 Pedal dimensions

When evaluating the pedal, 6061 aluminum was considered due to its malleability and easy access. It was proposed to carry out 3 studies in the ANSYS software in order to evaluate the vibration modes, the useful life behavior that the material will have and the loading forces that it will have. Table 2 shows the characteristics of the meshing used in the analysis carried out.

Analysis	Modal	Structural static
Aspect ratio (max)	6.3029	6.3029
Element size	7	7
Element type	Tetrahedron	Tetrahedron
Number of mesh elements	377446	377446
Element quality	0.99999	0.99999

Table 2 Meshing characteristics

Regarding the requirements for the analysis, Table 3 shows the boundary conditions that were considered for the pedal analyses. It should be noted that in the modal analysis only the fixations were considered while in the structural static analysis the loads that were used were used. were previously calculated. These values were stipulated due to the positioning of the pedal with respect to the vehicle. Figure 11 shows the approach graphically.

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Type of load / fastening	Value	Location
Force in the X axis	2000 N	Pedal pad
Force in the X axis	9619 N	Top hole
Cylindrical support	0 mm	Top hole
Cylindrical support	0 mm	Bottom hole

Table 3 Specification of location of loads and supports exerted on the pedal

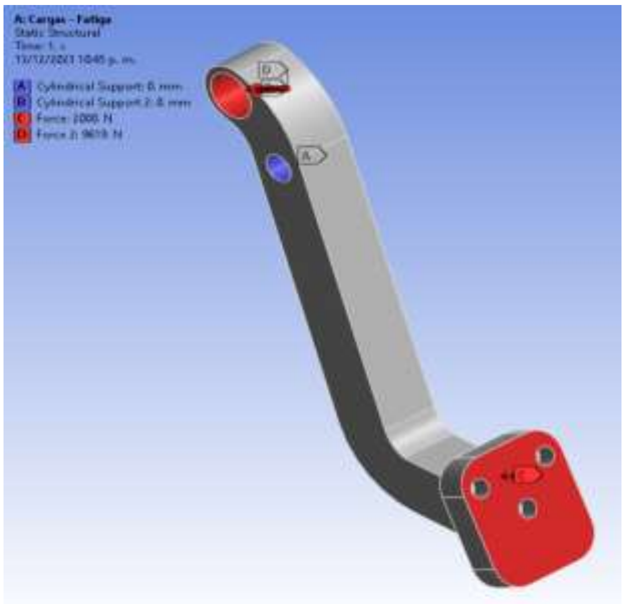

Figure 11 Global view of the pedal representing loads and supports exerted on the model for study

Initial model results

Structural

The total deformations presented by the loads described above are shown in figure 12.

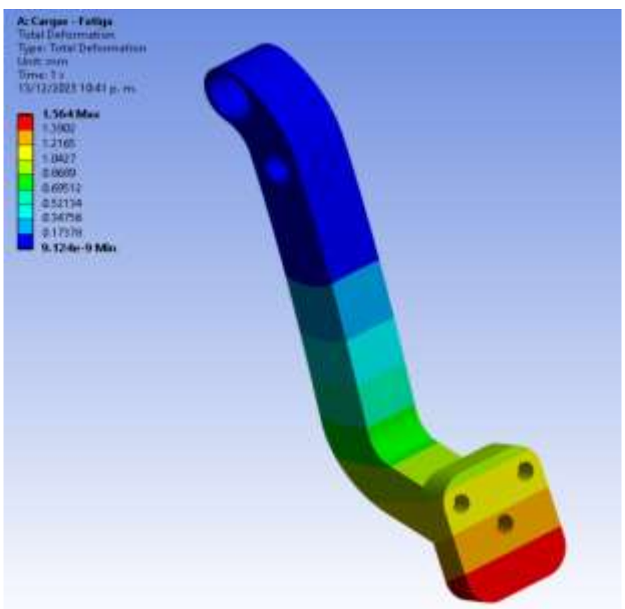

Figure 12 Global view of the pedal representing the results of the deformations due to the applied loads

The equivalent forces presented by the loads described above are shown in figure 13.

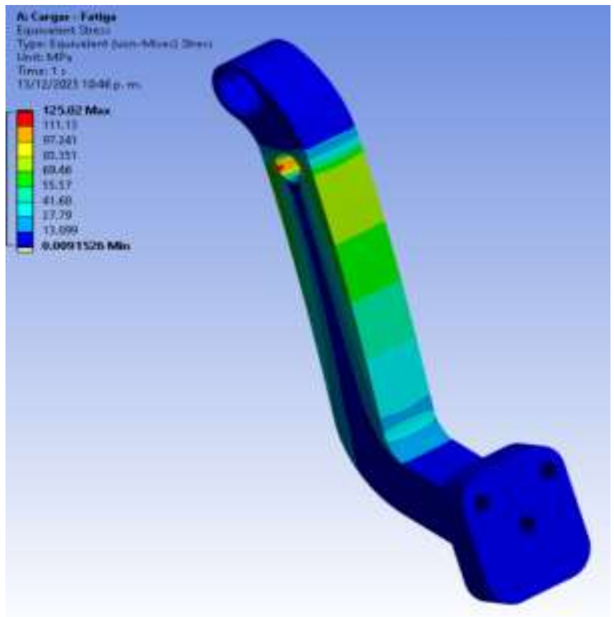

Figure 13 Global view of the pedal representing the results of the applied loads

As seen in Table 4, a maximum value of 1.564 mm was obtained in the total deformation, 0.0055919 mm in the directional deformation and 125.02 MPa in the equivalent stress, this based on the loads applied in the areas where the pedal is activated and where The force is multiplied by the effect of the lever arm.

Structural static analysis	
Type	**Value**
Total deformation	1.564 mm
Equivalent stress	125 MPa
Directional deformation	0.0055919 mm
Life	1e+008 cycles

Tabla 4 Resultados evaluación estática estructural

Fatigue

Figure 14 shows the results of the pedal fatigue analysis, a value of 1e+008 cycles was obtained, based on the stress-strain curve of the AL6061. The distribution of the cycles is observed globally throughout the geometry of the pedal, with very few points below this limit.

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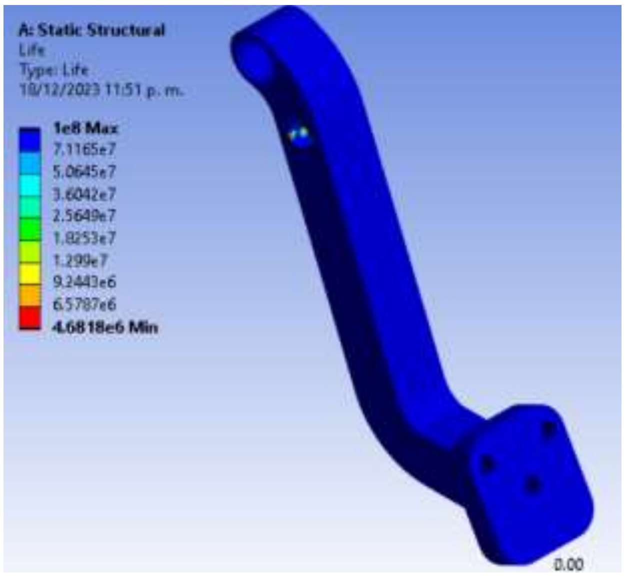

Figure 14 Global view of the pedal representing the results of the applied loads

Modal

For the modal analysis of the pedal structure, Figure 15 presents the different vibration modes of the analyzed structure. As part of this evaluation, the typical operating revolutions of the vehicle's engine were identified, for which its operating frequency was found to be 64.16 Hz.

Table 5 describes the numerical values found in the vibration modes of the structure.

BAJA engine working analysis	Vibration modes results	Numerical values in HZ
3850 rpm = 64.16 Hz	1	336.49
	2	347.06
	3	1192.6
	4	1443.6
	5	2526.3
	6	4624.2

Table 5 Modal evaluation results

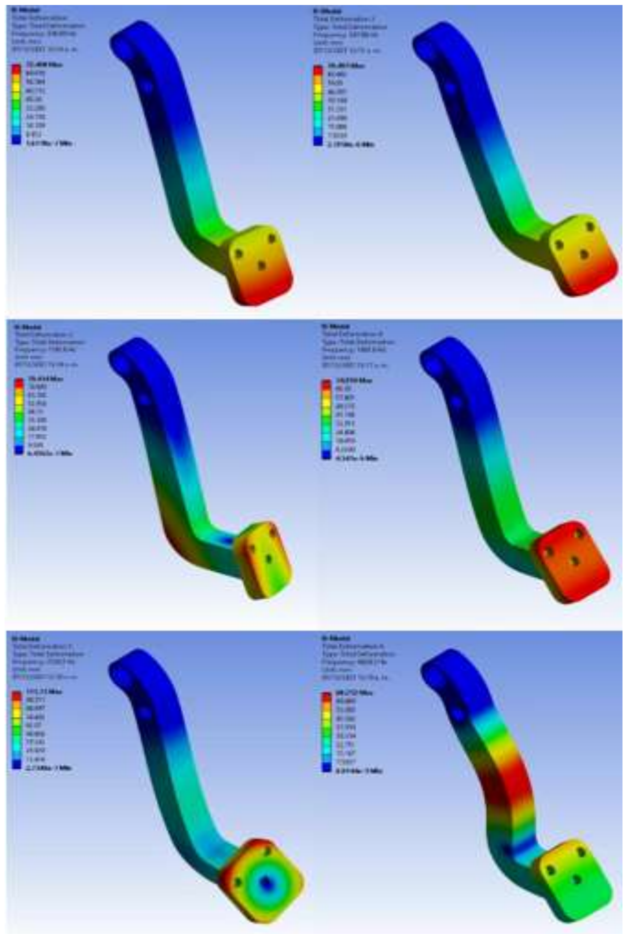

Figure 15 Modal evaluation results

Topology optimization

After evaluating the design of the brake pedal through the different studies presented, the topological optimization of the pedal was carried out, the analysis focused on reducing mass as a key factor. A target reduction of 30% of the original mass was set, with the aim of reducing weight inside the vehicle without compromising the function of the optimized elements.

Figure 16 shows the conditions under which the study was carried out. The areas where the forces and supports are placed in the structural static evaluation were taken into consideration, as well as areas where it is not of interest to eliminate material within the geometry.

Figure 16 Global view of the pedal representing topological region (blue A) and exclusion region (red A)

The analysis yielded a model with the topological density where an optimized design is shown in Figure 17.

Figure 17 Topological Density

Based on the results obtained in the topological optimization analysis, the change in the geometry of the pedal was made to reduce the weight. The proposed model is shown in Figure 18.

Figure 18 New pedal model proposal

In order to validate that the new pedal model met the requirements set out at the beginning of the document, the analyzes shown in the previous model were carried out again, taking into consideration similar conditions for the meshing and the same boundary conditions used with the original geometry.

Optimized model results

Structural

Figures 19 and 20 show the results of the total deformations and the stresses applied to the optimized geometry of the pedal.

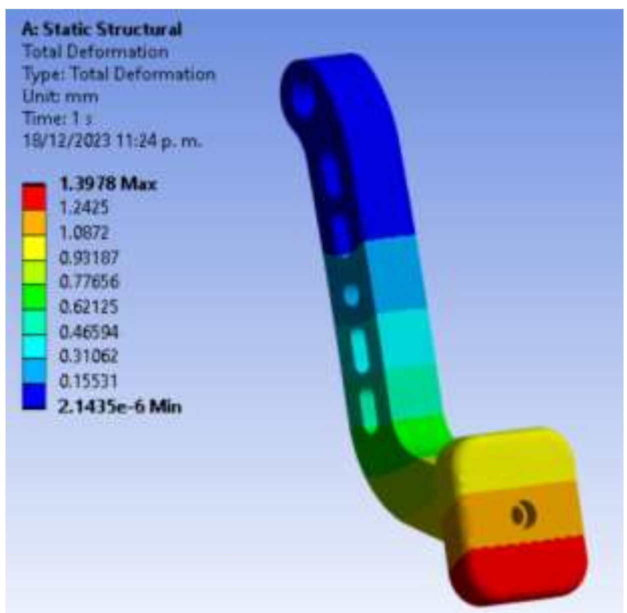

Figure 19 Global view of the pedal representing the results of the applied loads

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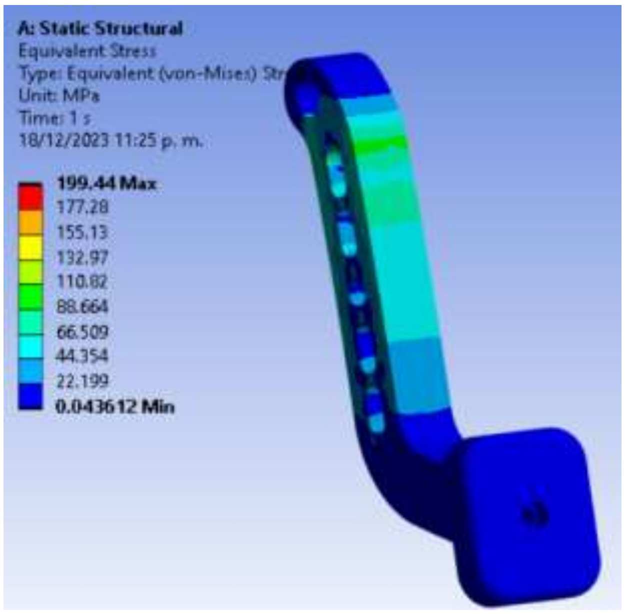

Figure 20 Global view of the pedal representing the results of the applied loads

Subsequently, the fatigue evaluation is applied with the same conditions, which is shown in Figure 21. In this result, variations are observed with respect to the previous analysis, especially in the minimum number of cycles to be fulfilled in some points.

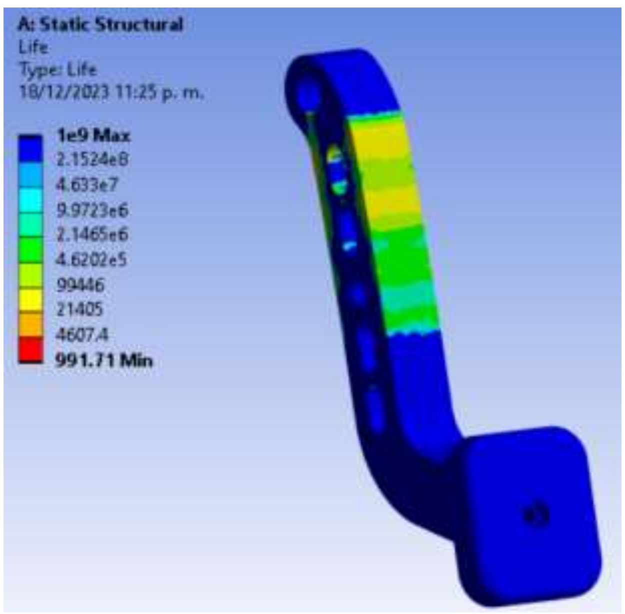

Figure 21 Global view of the pedal representing the results of the applied loads

As seen in Table 6, a maximum value of 1.3978 mm was obtained in the total deformation and 199 MPa in the equivalent stress, this based on the loads applied in the areas where the pedal is activated and where the force is multiplied by the effect of the lever arm.

Structural static analysis	
Type	Optimized model
	Value
Total deformation	1.3978 mm
Equivalent stress (276 MPa del AL6061)	199.44 MPa
Life	1e+009 cycles

Table 6 Structural static evaluation results

Modal

The modal evaluation of the optimized model was carried out, finding the results shown in table 7 and figure 22 of the different vibration modes.

BAJA engine working analysis	Vibration modes	Optimized model Numerical values in HZ
3850 rpm = 64.16 Hz	1	278.38
	2	373.47
	3	987.2
	4	1389.1
	5	2171.6
	6	4799.1

Table 7 Modal evaluation results

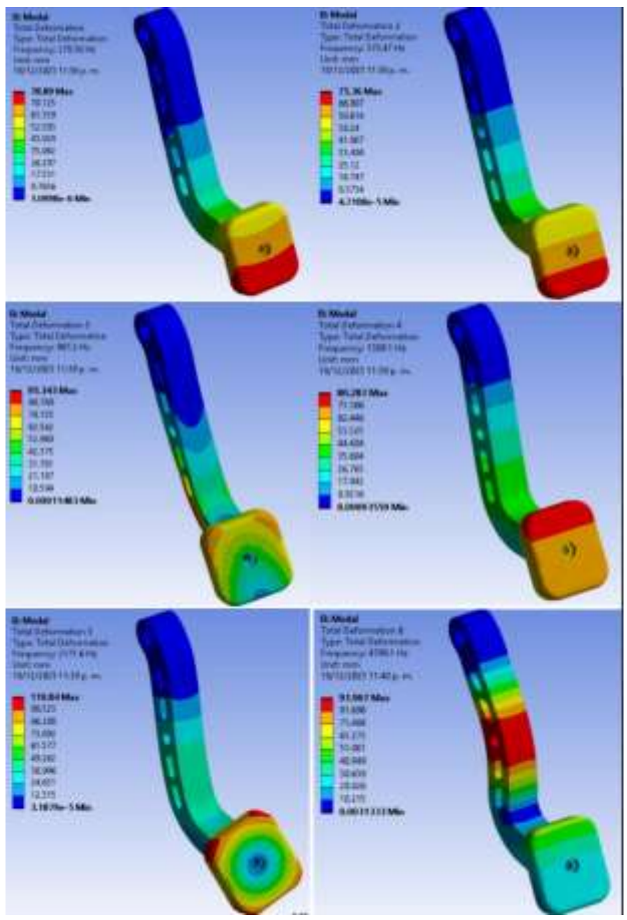

Figure 22 Global view of the pedal representing the results of the applied loads

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Conclusion and discussion

In the studies presented, the performance of the pedal structure was analyzed under three main studies, structural statics, operating cycles and modal evaluation.

Structural static analysis		
Type	Initial model	Optimized model
	Value	
Total deformation	1.564 mm	1.3978 mm
Equivalent stress (276 MPa yield of AL6061)	125 MPa	199.44 MPa
Life	1e+008 cycles	1e+009 cycles

Table 8 Structural evaluation results

BAJA engine working revolutions	Vibration modes	Initial model	Optimized model
		Numerical values in HZ	
3850 rpm = 64.16 Hz	1	336.49	278.38
	2	347.06	373.47
	3	1192.6	987.2
	4	1443.6	1389.1
	5	2526.3	2171.6
	6	4624.2	4799.1

Table 9 Modal evaluation results

As seen in tables 8 and 9, the results obtained between the initial proposal of the model and the final optimized geometry present a minimum variation taking into consideration the reduction of the material, this meets the objective of generating a lighter model but that I preserved the necessary properties so that the pedal does not fail and fulfills its function.

Of these three criteria, in the calculated values, it was found when comparing them against the requirements stipulated in the competition regulations that the pedal can perform its function without it failing when activated, in the structural static analysis parameters were calculated of total deformation which gave values which are minimal and do not affect the behavior or integrity of the pedal, in addition in the result of the Von-Misses criterion it was observed that the value did not exceed the yield limit of the material used for the pedal and as the last section of the structural static analysis, the number of operating cycles of the pedal was calculated, ensuring that the number of times the pedal was activated is not enough for the element to fail.

With respect to the topological optimization carried out, the objective of reducing the weight of the element studied, maintaining similar characteristics in terms of the behavior of the pedal and ensuring correct operation, as well as the elimination of possible failures due to the forces to which it was subjected during the BAJA SAE 2023 competition.

In the same way, Asanov [4] analyzed a model of a brake pedal under certain parameters, where it was analyzed whether the pedal is prepared to resist loads in a sudden braking process. Regarding these studies, there is a similarity in their approach having a force greater than that indicated in their investigation. As for future work, it could be the evaluation using certain failure parameters or even the use of another material and determining the dynamic behavior of the pedal.

Although this brake pedal was designed in accordance with the vehicles manufactured for the Baja SAE competition, taking into account the loads that the driver will apply to the pedal and the weight it must support in order to have correct braking performance.

This optimized model was manufactured and used in the 2023 competition and of which figure 23 is shown.

Figure 23 Baja SAE 2023 Vehicle Mounted Pedal

In future work, we will seek to maintain the resistance characteristics of the brake pedal by further reducing the weight through a different optimization, change of material or geometry, but improving the output force that is transmitted through the pedal to the hydraulic system.

Acknowledgements

The authors wish to thank the Popular Autonomous University of the State of Puebla for the use of the facilities and facilities provided in the development of this work.

Funding

This work was fully funded by the Universidad Popular Autónoma del Estado de Puebla A.C.

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