Article

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Analysis of the mechanical behavior of the chassis of a vehicle driven by human power through the application of the FEM module of a commercial CAD Software

Análisis del comportamiento mecánico del chasis de un vehículo impulsado por potencia humana mediante la aplicación del módulo MEF de un Software CAD comercial

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Abstract

In this paper, a design of a vehicle called Human Powered Vehicle (HPV) will be developed, which must comply with the competition requirements of the ASME standard, since it has as purpose in the future to participate in the student competition organized by this association (ASME). In order to achieve compliance with the objectives of the vehicle design, a process was followed, in which the first step was to know the requirements that the model to be made must have, in accordance with the standard, that is, both in terms of form and materials to be used. Three different structures were made, which met the requirements of the model. These models were simulated with finite elements to determine their viability, which were subjected to various static loads, among which are loads due to overturning, impacts; Likewise, the fastenings to which the system is exposed were considered, these fastenings were considered of the fixed type. According to the results obtained, the model meets the needs of the ASME standard, in addition to being a light and safe vehicle for the driver.

Vehículo impulsado por potencia humana, Análisis por elemento finito, Simulación

Resumen

En el presente trabajo se desarrollará un diseño de un vehículo denominado Vehículo impulsado por potencia humana (HPV: Human Powered Vehicle, por sus siglas en inglés), el cual debe cumplir con los requerimientos de competición de la norma ASME, ya que se tiene como propósito a futuro participar en la competencia estudiantil organizada por esta asociación (ASME). Para lograr el cumplimiento de los objetivos del diseño del vehículo se siguió un proceso, en el cual como primer paso fue conocer los requerimientos que debe tener el modelo a realizar, de acuerdo con la norma, es decir tanto de forma como de los materiales a utilizar. Se realizaron tres diferentes estructuras, las cuales cumplían con los requisitos del modelo. Dichos modelos se simularon con elementos finitos para determinar la viabilidad de ellos, los cuales se sometieron a diversas cargas estáticas, entre las que se encuentran cargas debidas a volcaduras, a impactos; así mismo se consideraron las sujeciones a las cuales el sistema está expuesto, estas sujeciones se consideraron del tipo fijas. De acuerdo con los resultados obtenidos se tiene que el modelo satisface las necesidades de la norma ASME, además de que es un vehículo ligero y seguro para el conductor.

Human-powered vehicle, Finite element analysis, Simulation

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Introduction

Nowadays, the environmental situation and human needs have led to the development of various alternative vehicle models, in which environmentally friendly energy sources are used as the system's propulsion source. Such is the case of human-powered vehicles. A human-powered vehicle (HPV) is a transport system developed as an intercity mobility alternative for journeys of 30 minutes or less, which aims to reduce emissions of pollutant gases into the atmosphere and consequently reduce the exposure of the population to these pollutants, improving their health and raising their quality of life (Johansson et al. (2017)).

There are some models (HPV), reported in the literature among which are; the vehicle designed by Fegade et al. (2018), which was designed taking into consideration criteria such as the aerodynamics of the chassis and the overall weight of the vehicle, for its part, Knaus et al. (2010) developed an HPV according to both the design criteria requested to participate in the Human Powered Vehicle Challenge (HPVC) competition sponsored by the American Society of Mechanical Engineers (ASME) and to economic, ergonomic and low weight criteria, which resulted in the development of a lightweight, high-speed and easy-to-repair vehicle. Similarly, Choudhury et al. (2012) proposed a human-powered vehicle capable of moving over a variety of uneven terrain by transferring the power generated by the occupant to the transmission system using a biodegradable hydraulic fluid. Most of the aforementioned vehicles were developed using design criteria focused on improving the performance of the vehicle when moving over various types of terrain, however, some safety criteria in case of collisions were not considered.

In this work we aim to design a human-powered three-wheeled vehicle that possesses both performance characteristics similar to other vehicles of the same type reported in the literature and safety criteria to safeguard the integrity of the occupant in the event of a rollover or a lateral collision. To corroborate the mechanical behaviour of the proposed vehicle chassis under the aforementioned loading conditions, a series of simulations based on finite element theory were carried out.

Design criteria

In order to meet the objectives initially set out within the project, a series of design criteria were proposed based both on the rules of the Human Powered Vehicle Challenge (HPVC) competition (American Society of Mechanical Engineers. (2021)) and on geometric and ergonomic criteria based on the anthropometric dimensions of the Mexican population in an age range of 18 to 25 years (Carmenate et al. (2014)).

Performance criteria:

- Braking distance less than 6 m, from a speed of 25 km/h to rest.
- Turning radius less than 8 m.
- Minimum steady speed of 5 km/h.

Safety criteria:

- Minimum distance of 2 in from the chassis to the ground.
- Minimum distance of 3 in between the rider's helmet and the top of the safety cage.
- Design of seat belt harness brackets in accordance with the criteria set out in SAE Baja, "Mini Baja Regulation 2020", (2020).
- Roll cage capable of withstanding a state of loading as described in Figure 1, without permanent deformation or deformation greater than 5.1 cm.

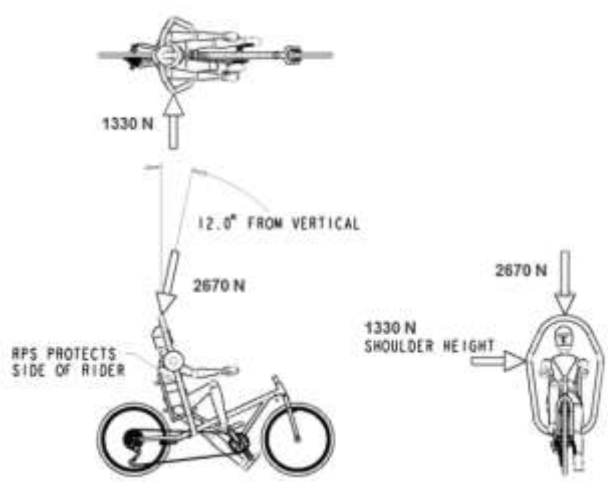

Figure 1. State of applied loads on the chassis
Source: (American Society of Mechanical Engineers (2021)

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HPV design description

For the design of the human-powered vehicle proposed in this work, a three-wheeled vehicle model with the "tad-pole" configuration was selected, which, consists of a vehicle equipped with two wheels on the front axle and one wheel on the rear axle (Kosmanis et al. (2014)), as shown in Figure 2.

Figure 2 First prototype of the proposed HPV

The tad-pole configuration allows both to distribute the driver's weight evenly over the vehicle chassis and to provide the vehicle with a rear-wheel drive system and front steering, thus reducing the risk of rollover, improving the vehicle's performance when driving on steep slopes and achieving a minimum stable speed well below 5 km/h.

For the design of the chassis, two types of tubular sections were considered; a 3/4" circular section of schedule 40, and a square section of 7/8" x 7/8" x 1/12". Both tubular sections were commercially manufactured using 6063-T6 aluminium. The first chassis design is shown in Figure 3.

Figure 3 Proposed chassis design

Table 1 shows the chemical characteristics of the selected material in weight % provided by the manufacturer (Aluminium (1100, 1200, 3003, 6026, 6061, 6063, 7075, Ladders), (2022)).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Otros	Aluminium
0.2-0.6	0.35	0.1	0.1	0.45-0.9	0.1	0.1	0.1	0.15	Rest

Table 1 Chemical characteristics of 6063-T6 aluminium in % weight

Similarly, Table 2 shows the mechanical properties of the material used as part of the boundary conditions of the simulation (Aluminium (1100, 1200, 3003, 6026, 6061, 6063, 7075, Stairs), (2022)).

Material	σ_U. (MPa.)	σ_y (MPa)	Elongation (%)	Hardness HB
Aluminium 6063-T6	245	215	14	75

Table 2 Mechanical properties of 6063-T6 aluminium

In the case of the wheels, transmission system and braking system, the commercial items described in Table 3 were selected.

Component	Quantity
Crankset Shimano RS2000	1
Shimano HG-31 cassette	1
26" rim, Double Fighter 3	2
20" rim, Double Fighter 3	1
Braking system Shimano BR-M6000	1
Brake disc Shimano Deore SM-RT56	2
Shimano shift lever SL-M315-8R	1
Shimano shift lever SL-M315-L	1

Table 3 Commercial HPV components

The seat was designed using a synthetic membrane attached to the chassis by means of a flexible fastening system consisting of coated steel cables.

Mechanical analysis of the structure

In order to analyse the mechanical behaviour of the proposed chassis under side impact and low speed rollover, a series of simulations based on the Finite Element Method (FEM) developed in the FEM module of a commercial CAD software were carried out. For this purpose, the Solidworks Simulation® module developed by Dassault Systèmes® was selected.

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According to the mechanical properties of the material, a mass of 9.44484 kg was considered for the chassis and taking as a reference the average mass of the Mexican population in an age range of 18 to 25 years, plus a safety factor due to the use of safety equipment and various accessories, a mass of 130 kg was considered for the pilot.

In the case of the side impact simulation, all degrees of freedom of the contact surfaces between the chassis and the tyres were restricted as shown in Figure 4.

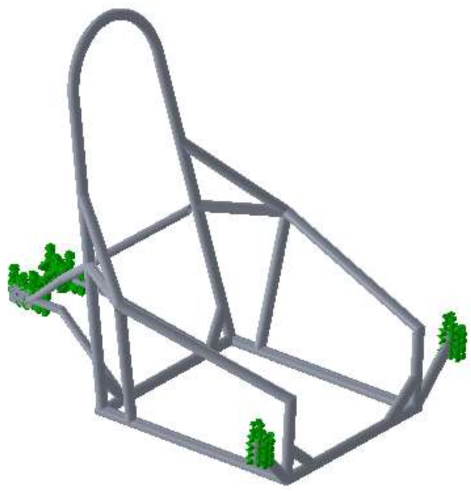

Figure 4 Constraints for side impact simulation

This means that both rotations and displacements of the chassis on the tyre contact surfaces are not allowed. Similarly, for the low-speed rollover simulation, all degrees of freedom of the surfaces where the seat belt supports are located were restricted. The surfaces where the seat belt mounts are located on the chassis are marked in green in Figure 5.

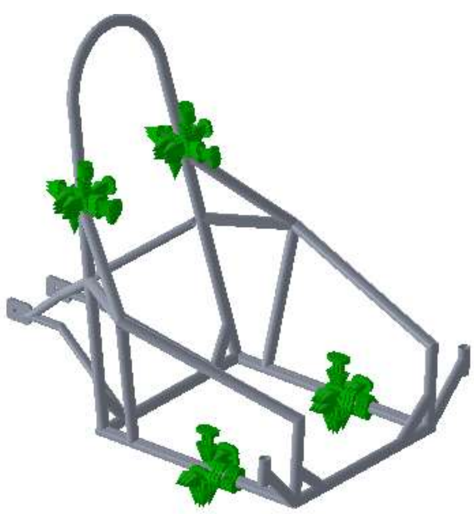

Figure 5 Constraints for low speed rollover simulation

Once the displacement restrictions were defined, the external forces acting on the chassis were introduced, taking as a reference the load state described in Figure 1. For the case of the chassis weight, the gravity force option, g, included in the simulation module was activated. For the weight of the rider, safety equipment and accessories, the total force, W, was distributed equally and applied to the surfaces where the seat supports are located as shown in Figure 6.

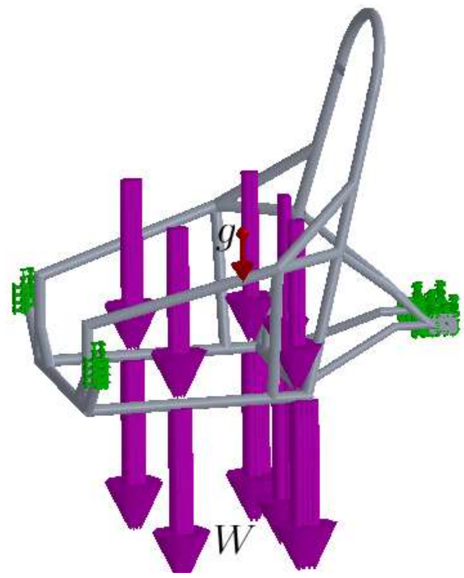

Figure 6 Application of pilot weight, safety equipment and accessories

The loading condition for the side impact simulation consists of the application of a horizontal lateral force, FL, of 1330 N as shown in Figure 7.

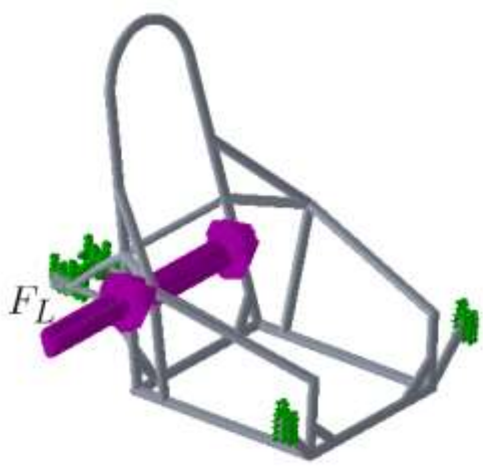

Figure 7 Loading state for the side impact simulation

Figure 8 shows the loading state used for the low speed rollover simulation, where the loading state described in Figure 1 is applied, consisting of a horizontal lateral force, FL, of 1330 N and a force, Fv, applied on the roll cage.

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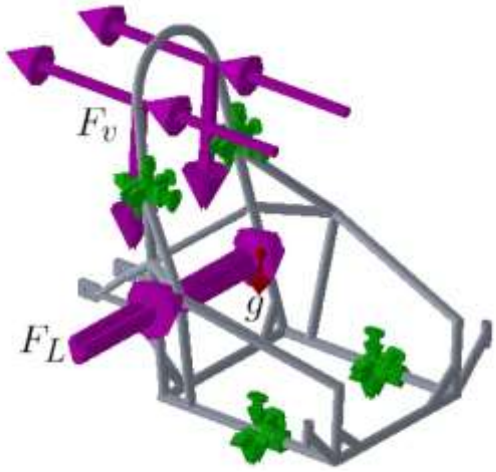

Figure 8 State of loads for the low speed rollover simulation

To generate the chassis mesh, a curvature-based mesh composed of high-order triangular solid elements with a maximum size of 28.9607 mm and a minimum size of 5.79213 mm was implemented. Figure 9 shows the resulting mesh, which consists of 148,003 nodes and 73,371 elements.

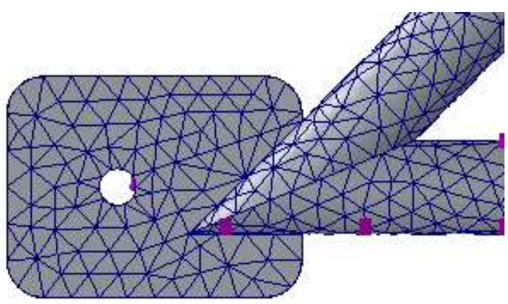

Figure 9 Fragment of the mesh used in the simulation..

Additionally, the option of large displacements and deformations was selected because the geometry analysed is non-linear. The "Direct Sparse" option was used as the solution method, which is recommended for systems with less than 100,000 degrees of freedom (Gómez-López et al. (2013)). As simulation results, the stresses and deformations to which the chassis is subjected under the load states described above were obtained.

Results

When performing the side impact and low-speed rollover simulations, it was found that the chassis design shown in Figure 3 presented deformations of more than 5.1 cm when subjected to a low-speed rollover, so a reinforcement was added to the roll cage as shown in Figure 10.

Figure 10 Final chassis design

With the final chassis design, simulations based on the finite element theory were again carried out considering the load states and displacement constraints described above. Both the maximum allowable deflection constraint and the Von Mises criterion (Von Mises (1913)) were used to analyse the results.

Lateral impact simulation

In the case of the simulation of the mechanical behaviour of the chassis when subjected to a side impact, a maximum deformation of 2.82 mm on the upper arch of the roll cage was observed as shown in Figure 11. This represents 5.52% of the maximum permissible deformation.

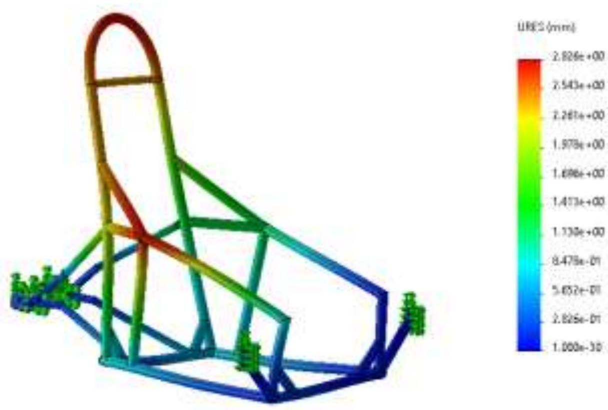

Figure 11 Chassis deformation under side impact

Similarly, Figure 12 shows the stresses to which the chassis is subjected during a side impact, the maximum stress value reached 103.1 MPa which is equivalent to 47.95% of the yield stress of the material.

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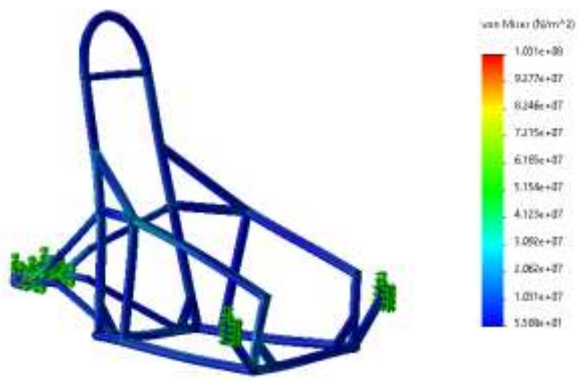

Figure 12 Chassis forces under side impact

Comparing the maximum stresses and deflections with the design criteria, it was found that the vehicle meets the safety criteria in the case of a side impact.

Simulation of low-speed rollover

The results of the simulation of the mechanical behaviour of the chassis in a low-speed rollover show a maximum deformation of 4.528 mm, equivalent to 8.87% of the maximum permissible deformation, as shown in Figure 13.

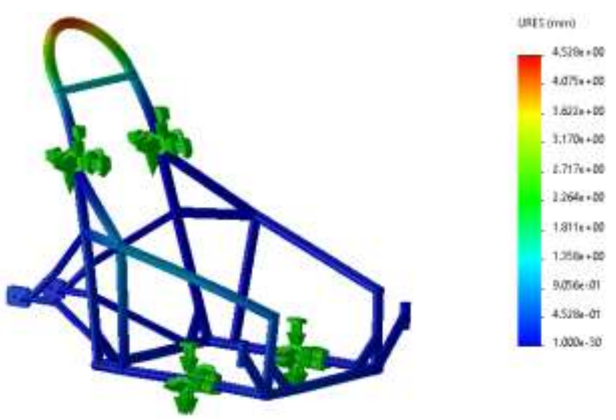

Figure 13 Chassis deformation in a low-speed rollover

The maximum stress shown in Figure 14, with a value of 132.0 MPa, corresponds to 61.39% of the yield stress of 6063-T6 aluminium.

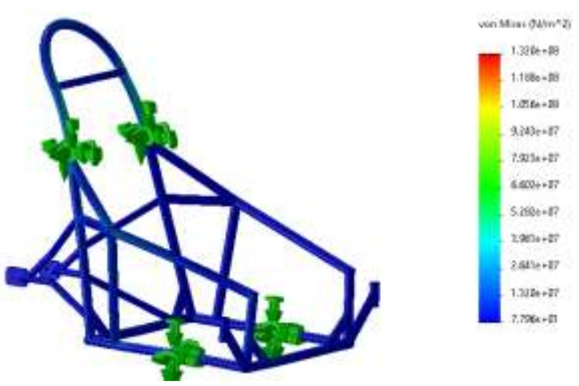

Figure 14 Chassis stress in low-speed rollover

Taking into consideration the values of chassis stresses and deformations, it can be said that the vehicle meets the safety criteria for a low-speed rollover.

Conclusions

This work presented the analysis of the mechanical behaviour of a chassis designed for a human-powered vehicle using a series of simulations based on the finite element theory by applying the Solidworks Simulation® module, which is part of the Solidworks® CAD software developed by Dassault Systèmes®. As a result of the simulations, it was found that the first design proposed for the chassis did not meet the safety criteria by presenting a deformation of more than 5.1 cm in the upper arch of the roll cage when subjected to a state of loads that emulates a low-speed rollover.

Based on the distribution of stresses and deformations, it was proposed to add reinforcement to the roll cage in order to reduce the deformations and alter the stress distribution and thus reduce the magnitude of the maximum stress. By simulating the new chassis design with the proposed material, it was found that it meets the safety criteria when subjected to both side impacts and low-speed rollovers. In both cases the stress magnitude is within the elastic range of the material and the deformations were much smaller than 5.1 cm.

Furthermore, taking as a reference the distribution of stresses and deformations in the chassis, their magnitude and the elastic limit of the material proposed for its manufacture, welding can be considered as a method of joining the various substructures that will form the chassis without significantly affecting the mechanical behaviour of the chassis.

Acknowledgements

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