

# Testing Oscillation and Optimization of the Motorcycle Frame Body Using Co-Simulation Method

Khảo sát dao động và tối ưu khung xe máy sử dụng phương pháp mô phỏng kép

**Thanh-Tung Tran<sup>1\*</sup>, Quang-Tuan Hoang<sup>1,2</sup>**

<sup>1</sup>Hanoi University of Science and Technology, Hanoi, Vietnam

<sup>2</sup>Hanoi University of Industry, Hanoi, Vietnam

\*Email: tung.tranhanh2@hust.edu.vn

## Abstract

The article is devoted to researching the durability of motorcycle frames with calculated loads in some cases of actual vehicle operation based on Vietnamese standards. The paper uses the multi-body system method to build a dynamic model suitable for the actual test problem according to the standard and optimize the mass of the motorcycle frame by the finite element analysis. The study includes an overview and analysis when choosing a motorcycle frame commonly used in Vietnam. A motorcycle frame of Wave brand is used to calculate and test the chassis durability with different parameters. Various internal loading modes are applied to the multi-body system model to help optimize the vehicle chassis mass by using specialized software. The authors calculated the load, built a durability model with static loads in practical working situations, built a multi-object system model to investigate the vehicle dynamics problem with the standards. This paper leads to the problem of optimizing the chassis thickness to reduce the weight of the chassis. Computers and optimization tools help engineers to save much time in the product design process. Investigating product optimization helps solve problems quickly, finding the best design, assisting engineers in developing the best strategies, and reducing time and costs during prototyping and testing.

Keywords: Oscillation, suspension system, optimization, co-simulation, motorcycle frame body.

## Tóm tắt

Bài báo nghiên cứu độ bền của khung xe máy với tải trọng tính toán trong một số trường hợp vận hành xe thực tế dựa trên tiêu chuẩn Việt Nam. Bài báo sử dụng phương pháp mô hình hóa hệ nhiều vật để xây dựng mô hình động lực học phù hợp với bài toán thử nghiệm thực tế theo tiêu chuẩn thử nghiệm và tối ưu hóa khối lượng khung xe máy bằng phương pháp phần tử hữu hạn. Nghiên cứu lựa chọn đối tượng phân tích theo khung xe máy thường được sử dụng tại Việt Nam. Khung xe máy hiệu Wave được sử dụng để tính toán và kiểm tra độ bền khung xe với các thông số khác nhau. Nhiều chế độ tải bên trong khác nhau áp dụng cho mô hình hệ nhiều vật và ứng dụng nghiên cứu tối ưu khối lượng khung xe bằng phần mềm chuyên dụng. Các tác giả đã tính toán tải trọng, xây dựng mô hình mô phỏng kiểm bền tĩnh trong một số điều kiện làm việc thực tế, xây dựng mô hình hệ nhiều vật để khảo sát bài toán động lực học xe theo tiêu chuẩn. Bài báo hướng tới giải quyết vấn đề tối ưu hóa độ dày khung xe để giảm trọng lượng của khung xe. Sử dụng máy tính và các công cụ tối ưu hóa trên phần mềm, giúp các kỹ sư tiết kiệm chi phí đáng kể trong quá trình thiết kế sản phẩm. Nghiên cứu tối ưu hóa sản phẩm giúp giải quyết vấn đề nhanh chóng, tìm ra thiết kế tốt nhất, hỗ trợ các kỹ sư phát triển các chiến lược tốt nhất, giảm thời gian và chi phí trong quá trình tạo mẫu và thử nghiệm.

Từ khóa: Dao động, hệ thống treo, tối ưu hóa, mô phỏng kép, khung xe máy.

## 1. Introduction

Motorcycle frame is made from essential components such as rider support, engine support, suspension system, handlebars, and many other features such as fuel tank, etc. The proposal of chassis production is light, strong, and durable. Furthermore, motorcycle frames were developed with a variety of materials and they are usually made of aluminium, steel, or alloy. Although many types of materials are used to make frames, only a few satisfy the factors of

price, mechanical properties, weight, and some other points.

First, the chassis must avoid breaking the structure, however, the suitable material's maximum deformation and maximum stress should be considered. Metals have good mechanical properties (resistance, hardness, and strength), good electrical and thermal conductivity, ease of formability, and the ability to acquire other properties suitable for heat and unique treatments. Steel frame has good rigidity (large

elastic limit), easy to process bending, welding, cutting, and a low cost compared to other materials. The ease of machining makes it capable of mass fabrication. However, steel is heavy and susceptible to corrosion. Steel frames are made of hot or cold-rolled steel. Hot rolled steel is formed while hot steel and an oxidizing layer form on the outside of the bar, creating a rough, black surface. Its surface is not necessarily smooth or flat. Cold rolled steel is formed at low temperatures and has a smooth surface. It tends to be stronger than hot-rolled steel but is more challenging to fabricate.

Based on many survey options that have been carried out and within the limits of untested simulation research content, the article proposes the following survey plan using a 3D model of the motorcycle frame by software SolidWorks. The reference parameters are from the actual Honda Wave 110 series. The material used in the model is A710C steel. The construction of the finite element model and the author's calculations used HyperWorks software copyrighted by Altair. Analysis with static and dynamic loads was carried out to evaluate and test the quality of materials for vehicles manufactured in Vietnam. The study also developed an optimal calculation of the weight of the motorcycle frame but still ensured the standards durable will. The limitation is that it is only at the optimal survey and analysis simulation, without testing in processing and manufacturing.

One of the ways to solve the problem of simulating unconstrained objects is to use simulation combinations. Combined simulation or Co-simulation is the term used to refer to simulations of 2 or more solvers. Each solver will deal with a particular problem then a combination of the results will give more accurate results by taking advantage of each solver. In the field tool possible with the frame machine object, the method that can be applied may be Finite Element Analysis methods (FEA) combined with the multi-body systems approach (MBS). The FEA will be used to construct the frame owner element. The frame's computational stiffness, the frame marking system, and various information associations are available for use in the MBS. MBS is used to build a suspension system model to solve the problem of handling suspended under load from the road. The extracted results include inversion calculations on the model's FEA frame.

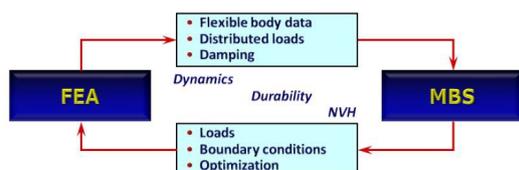


Fig. 1. The fundamental relationship between FEA and MBS

Fig. 1 shows the application of a flexible body which is confirmed in many previous studies. Bipin Chadha and Om Prakash Agrawal from Illinois Southern University, USA, used the flexible body model in their research to obtain more accurate results in assessing the vibrational state of the vehicle with excitation from different transmissions through the suspended system [1]. This study presents the most basic concepts using the flexible body model in an MBS problem. The softened object in the model is a Spartan chassis. Instead of being a body with six essential degrees of freedom, the parameters of a flexible body have been developed to help the body deform with many other degrees of freedom, thereby improving the accuracy of the results. In another study conducted by Jan Dizon and Miroslav Blatnicky, the applicability of the flexible body in the MBS system is confirmed by the computer tool's powerful ability. Research has shown that the accuracy of loose bodies is increasingly improved thanks to the development of computer hardware that allows calculations with models with many elements and complex shapes. This research contributes to bringing the simulation closer to reality, reducing assumptions in the analysis [2]. Optimization is the best result obtained or achievable under specific conditions, which the designer can freely change, like creating mathematical equations that can evaluate design efficiency. The quantitative parameter used to evaluate a design is called an objective. According to design requirements, we can set multiple objectives. Sometimes the goals can be contradictory, such as good quality, safety, and low cost. This research makes designers need to optimize numerous objectives before proceeding with the design [3]. Some parameters may not be allowed to change during design: the material may be restricted by factors beyond control, such as steel plates limited by commercially available thickness. The parameters that can freely change are called design variables [4].

## 2. Testing Oscillation Methodology

### 2.1. Forces Applied on Motor Frame Body

Reviewing the entire frame can take a long time because many different concepts are considered, such as shape, material, force, etc. Therefore the project implementation will be simple: we will simplify some aspects but still ensure the required results. For this reason, even though a motorcycle consists of many different mechanical parts, it will be considered a rigid system, and the whole vehicle will be defined as a spatial system composed of four pieces of hardware as follows.

The rear parts are the frame, saddle, fuel tank, engine, and transmission. Front units are a fork, steering shaft, and handlebar. The motorcycle has front and rear wheels.

The forces on the wheels will act directly on the frame. The calculated values will be much higher because when the suspension is inactive, the factor of safety will be lower than usual. Still, the structure will be rated in more severe conditions. Therefore, if the chassis is safe under these conditions, it will undoubtedly be safe under normal conditions.

A force from the rear wheel pushes directly on the frame. There is a connecting rod between the shock absorber, swingarm, and structure.

During work, the vehicle's center of gravity is never fixed. When the car accelerates, the center of gravity tends to shift backward, while in braking, it tends to move forward. Meanwhile, when entering bends, the center of gravity tends to lower. In addition, the fuel level also affects the center of gravity. We use the fixed center of gravity position to calculate the static load within the project limits [5].

Load changes during acceleration and braking are considered constant.

Note that safety is highly dependent on factors such as stress, fatigue, vibration and noise, and the generated deformations.

Fig. 2 shows a physical model of the frame with wheelbase, offset, and caster angle, which is taken as reference values from Honda Wave 110 series:

- wheelbase equal is 1224 mm with an offset of 25 mm;
- caster angle is 27 degrees;
- wheel diameter equals 440 mm;
- bodyweight equals 97 kg.

The driver's mass is considered load acting on the chassis at the driver's center of gravity. The road surface is flat and has a good grip, ignoring the phenomenon of tire slip during acceleration and braking.

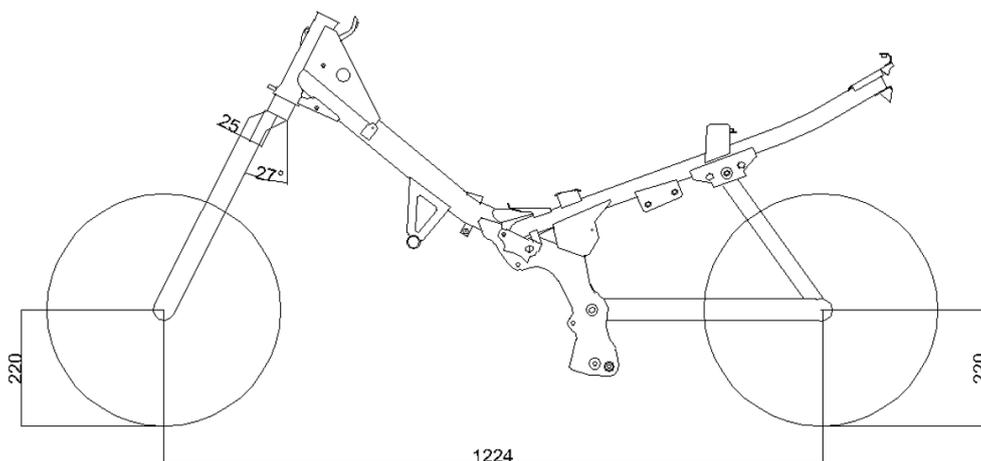


Fig. 2. Overview of chassis dimensions.

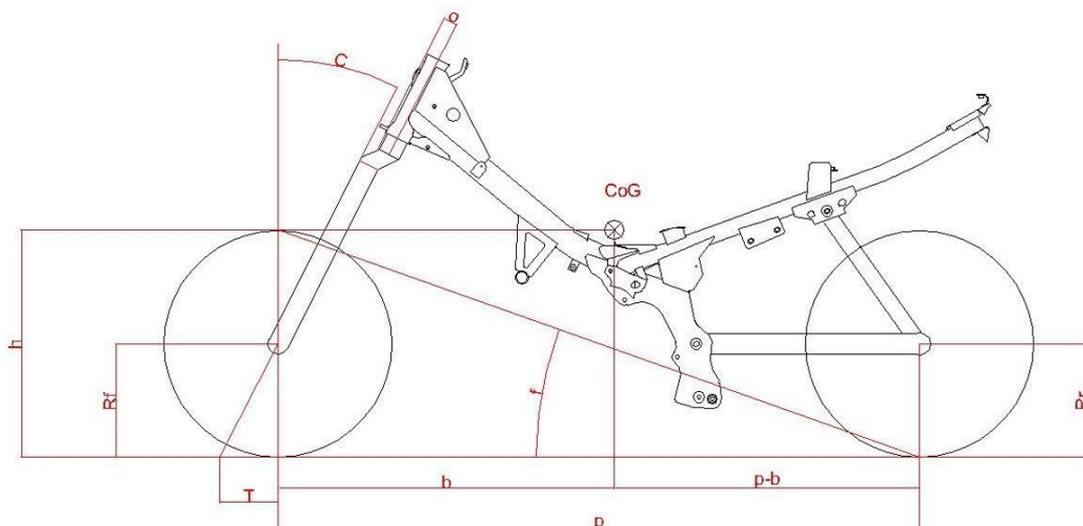


Fig. 3. Chassis parameters

Loads are calculated with maximum effect on the frame structure under different conditions. This result is vital to determine the parameters and conditions as shown in Fig. 3, including:

- Maximum acceleration
- Maximum brake front wheel
- Rear-wheel maximum brake

The parameters of the chassis are given in Table 1.

Table 1. Chassis parameters.

Symbol	Parameter
$p$	The standard long
$b$	Centre of gravity distance to the front axle
$p-b$	Distance from center of gravity to the rear axle
$R_f$	Front-wheel radius
$R_r$	Rear-wheel radius
$h$	Centre of gravity
$c$	caster angle
$o$	Offset distance
$T$	Trail distance
$f$	Load transfer angle
$CoG$	Vehicle center of gravity

### 2.2. Modelling the Suspension System

The suspension system on a motorcycle has a relatively simple structure, with a telescopic front and a cylindrical spring at the rear. The suspension system will refer to two primary elements: elastic – damping on both sides and a balanced position in the middle. Other suspension components include the front, rear, and non-suspension described by rigid bodies [6].

Now, the description is complete and the suspension system and flexible body model are combined to create the overall vehicle model, as shown in Fig. 4, 5, 6. The links between the suspension and the flexible body are also described.

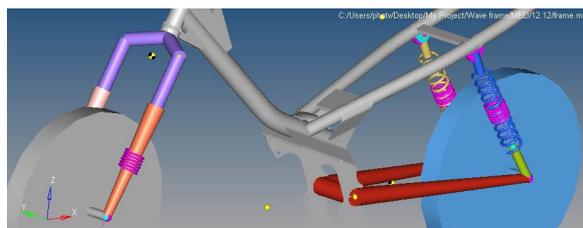


Fig. 4. Suspension model

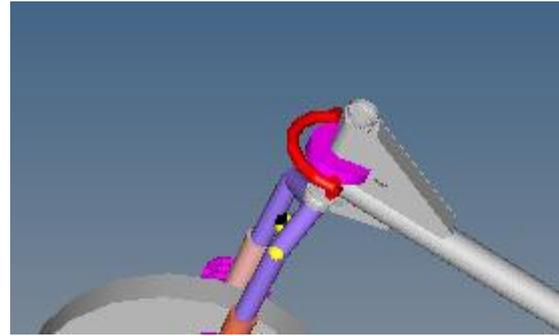


Fig. 5. Degrees-of-freedom restricted rotation connection between the front fork and collar

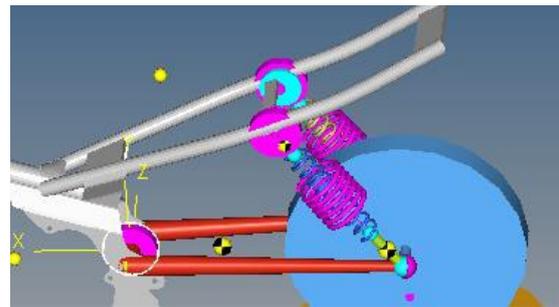


Fig. 6. Rear suspension swivel link

### 2.3. The Shaker Model Creates Oscillations for Chassis

The dynamic load calculated according to Vietnam Standard number 30 in 2010 (QCVN 30 – 2010) is shown in Fig. 7.

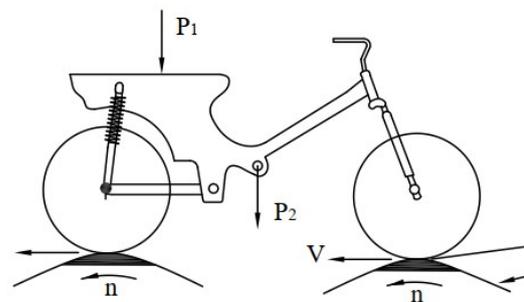


Fig. 7. Dynamic load model according to QCVN 30

The parameters for the model are:

- $P_1$  maximum vehicle design load
- $P_2$  engine weight
- $V$  velocity
- $n$  revolutions per minute
- Cam lug height from 15 to 25 mm
- Testing roller diameter: more than 750 mm
- The number of cam lug: more than 2

*Scope of regulation:* This regulation regulates the inspection of technical safety and quality for motorcycle and two-wheeled motorcycle frames (in

the future referred to as chassis). This standard is not applied to motorcycles and motorcycle frames used for security and defense purposes.

*Subjects of application:* This regulation is applied to establishments that manufacture and import vehicle frames, manufacture and assemble motorcycles and motorbikes, and agencies and organizations related to testing and inspection of quality certification and technical safety.

Following this standard, we can apply the excitation equation on the model as:

$$Fz = 25 \cdot \sin(4\pi t) \quad (1)$$

The movement of the roller by placing adjustable height platforms is shown in Fig. 8. Each shaker is assigned a motion translated in the z-axis, using a translational joint contact between the lift table and the wheels defined by reference.

The vibration assigned to the shaker is calculated according to the following assumption: The above condition determined that the oscillation would assign to the shaker with the sine form with the equation (1). The overall model for dynamic load calculation is shown in Fig. 9

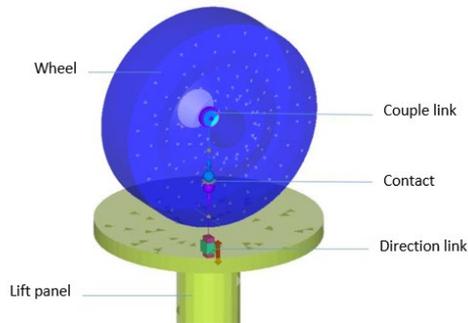


Fig. 8. Contact model of lifting table, wheel.

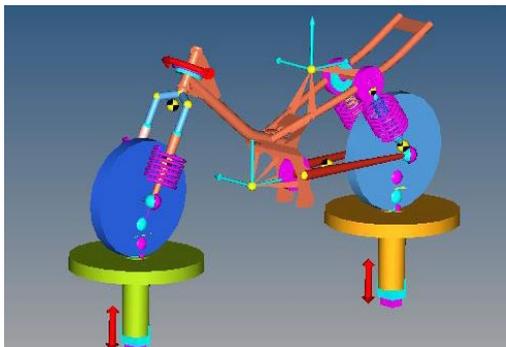


Fig. 9. The overall model of dynamic load calculation.

### 2.4. Simulation Result Discussion

The rest keep the simulation if it flicks at the first 2 seconds. From the 2nd to 3rd seconds, the lifting tables will gradually raise to each wheel's corresponding initial position. We will be interested

only in the main survey area in the survey results, from the 3rd second onwards.

The simulation results in Fig. 10 and 11 show displacement and stress distribution effects at  $t = 4.12$  s.

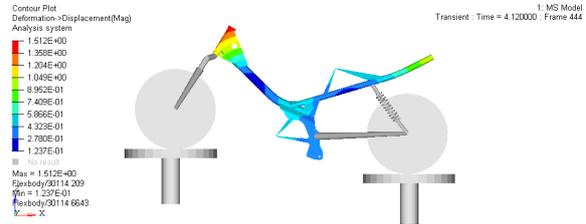


Fig. 10. Displacement of the chassis at 4.12 s.

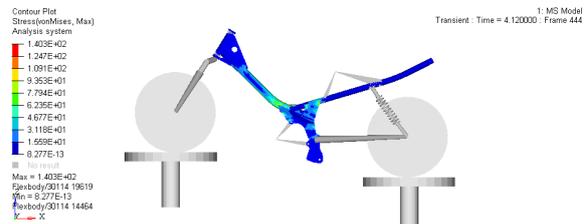


Fig. 11. The stress of the chassis at 4.12 s.

In this case study, Fig. 12 and 13 show the displacement and stress variation over time at element 2865, where is the maximum stress calculated from analysis simulation occurs. These results shown in the below figures are verified by the value of MBS at the model testing system.

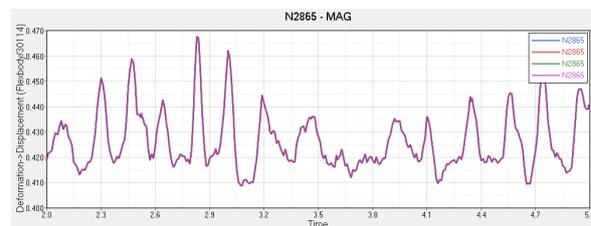


Fig. 12. Graph of displacement distribution over time (element 2865).

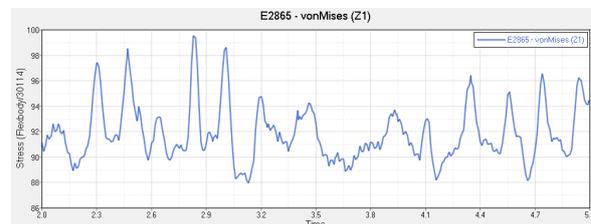


Fig. 13. Graph of stress distribution over time (element 2865).

These results showed that MBS could be helpful to solve some simulation problems as fatigue testing system, dynamics analysis system, or optimization system by using an output database. This paper uses these results as input data to solve the optimization problem for the motor frame body in the following section.

### 3. Simulation Optimization Methodology

#### 3.1. Optimal Design Method

The goal is to find a better design plan than the one from the start. It is possible to find the best option in some cases, while in others, it is not.

In the theory of optimization, the goal is to find the optimal values of the objective function. Each function has a minimum value in the optimization domain called a convex function. In the calculation, the minimum value of a curve is characterized by a zero slope. If the objective function is a quadratic function of design variables, this smallest value can be found since the quadratic function has only one extreme point in design space.

The higher-order curve may have many extreme points in design space. This research supposes that the function will have many minima and the decisive moment at which the objective function has the smallest value is the global minima, while the others are the local minima.

In fact, the problem can have hundreds or thousands of design variables. Moreover, the objective function can be a non-convex function, with lots of local minima in the design space.

Optimization software for giving a good answer in a reasonable time, OptiStruct, uses an iterative approach known as the local approximation method to solve optimization problems. The algorithms to set up an optimization solving motorcycle problems can be described in the following steps:

Step 1: Analyzing physical problems using FEM;

Step 2: Checking the convergence;

Step 3: Response screening to retain the active responses allowed for the current iteration;

Step 4: Analyzing the design sensitivity of the filtered responses;

Step 5: Optimizing the problem built up by the sensitivity information.

Step 6: Go back to step one.

To achieve stable convergence, the design variables that change in each iteration are limited to a small, limited range, called the move limits. The most significant change of design variable occurs in the first few iterations; based on advanced formulas and other stability measures, convergence for practical application is usually calculated with few FE analyses.

Design sensitivity analysis calculates the derivative of structural responses over design variables. Determining the sensitivity is an essential step to automate the calculation process.

Design updates are generated by solving an explicit approximate problem based on sensitive information. OptiStruct has two levels of improved optimization methods: dual method and simple method. The dual method solves problems in the dual space of Lagrange multipliers that involve positive constraints. It is highly effective for problems involving many design variables but with few constraints (a common method for topology and topography optimization). The simple method searches for the optimization in the original design variable space. Problems involving many constraints and design variables should require a general method for size and shape optimization. The software will automatically select the solver based on the properties of the optimization problem.

#### 3.2. Setting the Optimal Problem

For linear problems, defining a design optimization problem indicates the design space, design variables, constraints, and objectives. The appropriate mathematical expression is:

Find the smallest value:

$$f(x) = f(x_1, x_2, x_3, \dots, x_n) \quad (2)$$

Meet the following conditions:

$$g_j(x) \leq 0, j = 1, 2, \dots, m \quad (3)$$

$$x_i^L \leq x_i \leq x_i^U$$

where  $f(x)$  is the objective function,  $g(x)$  is the constraint function, and  $x$  is the vector of the design variables.

*Consider the following example:* The lightweight frame design should accommodate 300 mm x 300 mm x 600 mm dimensions. The frame is made of steel, load capacity of 100 kg. The maximum allowable displacement of the frame is 0.1 mm, and the maximum allowable stress is 20 kg/mm<sup>2</sup>. It is allowed to use steel plates that can be 1 mm, 2 mm, or 4 mm thick.

The goal will be to minimize the mass so that the optimization constraints will be the allowable stresses and displacements. The design parameters will be the thickness of the steel and the parameters for welding the details together in the frame structure, specifying the positions in the force application in space.

The first step is the optimization process from the original shape. The analysis software evaluates the object's mass, stress, and strain - values calculated by the analysis program and analyzed by the optimization algorithm with the response method. The optimization process evaluates the sensitivity of responses to different design variables, deciding what and how much to change.

As the design parameters change, the responses also change. If the thickness of the steel changes, the mass of the frame changes. Displacement will change significantly, and stress will also change. Therefore, the re-optimizer needs to request a re-analysis to re-evaluate the responses. This process will continue iteratively until the optimizer finishes and results in the best design for the model constraints and parameters.

### 3.2.1. Evaluating sensitivity

Evaluating bias to change design variables is an essential part of the optimization process. The response quality is calculated from the displacement as follows:

$$g = q^T \times u \quad (4)$$

The sensitivity of the design variable  $x$  or the gradient of the response is reflected in the equation below:

$$\frac{dg}{dx} = \frac{dq^T}{dx}u + q^T \frac{du}{dx} \quad (5)$$

Some design problems have more constraints than design variables, while other issues have more design variables than constraints.

### 3.2.2. Convergence of the Process

Because the optimal solver searches in the design space, it is necessary to check the boundary conditions to know if the problem converges; the authors use HyperWorks software with the Global Search method. When completing the optimization problem, it is necessary to determine whether the optimal solution achieved is the local or global optimum. Research method based on local approximation (Local approximation based) is often used to find the local maxima, so it is not guaranteed that it is the true global optimum. Global optimum occurs if and only if the problem is a convex function. However, models are challenging to build algorithms with convex functions in practice, so it is impossible to solve the global optimization problem fully. Therefore, the proposed algorithms aim to optimize each part of the problem instead of solving the overall optimization problem. This is a way of studying zoning in the simulation and experiment, in which the researcher needs to limit the areas for optimization problems and provide boundary conditions suitable for the research object and purpose to increase simulation time. The theory of this section is described through the example below, emphasizing the concept of the convex function problem, which is a convex optimization problem with a minimum or a maximum point.

In the case of a problem without a convex function, shown in Fig. 14, it is solved using gradient-based techniques. It makes local optimum finding algorithms easier using Hyperwork software using multiple starting point optimization approaches. This

algorithm can extend the search in the design space to find many overall optimal points. Based on the initial design starting point, there can be many different optimal solutions. It is also possible that different design starting points also produce overlapping optimal solutions, but it does not solve the overall optimization problem.

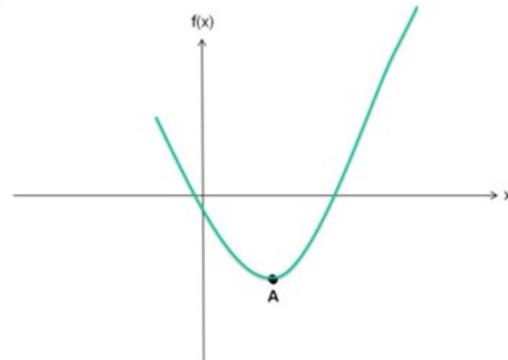


Fig. 14. Graph of one extreme convex function

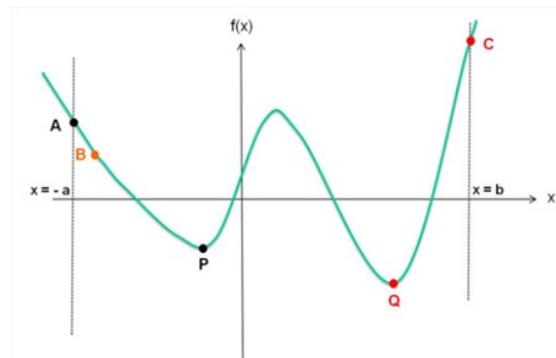


Fig. 15. Graph of convex function with many extreme points

Consider the non-convex function  $f(x)$ , bounded by  $-a < x < b$ , shown in Fig. 15. Optimizing a design from the design start point A to point P will be a locally optimal algorithm. Similarly, optimizing a design from design starting point B will also converge at P. On the other hand, optimizing a design from design starting point C will have optimal results at Q. Hence, there will be many optimal points not found from the model due to choosing the initial points and the optimal algorithm when studying. From a design perspective, finding optimal areas is important. First, it is possible to order a time-optimized solver for the number of iterations to evaluate the quality, find the point of convergence, and then find the maximum number of iterations. In addition, it is setting error threshold values which can also indicate how to find exactly how, for example, the displacement limit or allowable stress limit of the material. If the difference between two adjacent iterations is less than the convergence tolerance, then the problem can be concluded that the optimal method is accepted.

### 3.2.3. Regular Convergence Methods

There are two types of convergence tests used in OptiStruct and it is required that only one of the following conditions be satisfied.

Regular convergence is achieved when the convergence criterion is satisfied with two consecutive iterations. It means that for two consecutive iterations, the change in the objective function will be less than the target tolerance and the constraint violations less than 1%. It is required that at least three analyzes be performed for regular convergence when convergence depends on the comparison of the actual objective value: the value obtained from an analysis at the near design point Best. It is not feasible by design that when the constraints violate more than 1% and for three consecutive iterations, the change in the objective function is less than the target tolerance, and the change in the constraint violations is more minor than 0.2%. In this case, the temporary optimal result is accepted, and the loop evaluation is unnecessary.

Weak convergence is achieved when there is little or no change in the design variables in two consecutive loops. It is unnecessary to evaluate the goal or constraint for the final design point when the model is constant from the previous iteration. Therefore, weak convergence requires one iteration less than regular convergence.

### 3.2.4. Gradient Search Methods

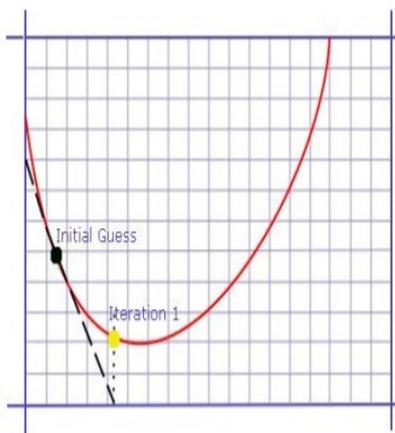


Fig. 16. Gradient method.

Fig. 16 showed that the method uses the slope of the curve to adjust the direction that was initially predicted to increase or decrease. The gradient search method also called the method of steepest descent, is one of many methods used by the optimizer to move from the initial solution to the final solution. It starts from an assumption for optimal design. From this point, the maximum decreasing direction of the objective function will be calculated based on the gradient of the objective function. Then searching moves as far as possible in this direction before repeating the process. The iteration is repeated and

convergence occurs when the gradient of the objective function is zero.

## 4. Optimizing Motor Frame Body Thickness with Free Size Optimization Module.

### 4.1. Initializing the Problem

In the calculated cases, the maximum equivalent stress value of the chassis is much smaller than the material's yield stress. The optimization of frame thickness without changing the stresses or insignificant changes does not affect the frame's durability but saves the material of the frame.

The maximum acceleration case has the most significant equivalent stress in the computational cases with the above static loads. Optimization is done through the load and boundary conditions that are applied to the case.

*Optimal conditions:* Since the stress value is much smaller than the yield stress value in the calculated cases, the optimal problem performed with the maximum stress constraint equal 70% of the yield stress. The process of creating design variables, binding functions, and goals is as follows:

Design variable: Chassis thickness

Constraint: maximum stress value:

$$\sigma_{max} = 0,7 \times 550 = 385 \text{ MPa.}$$

Objective: minimum chassis volume.

### 4.2. Optimization Results

Fig. 17, 18, and 19 show results after running the optimal problem that gave the thickness of the sections in turn as follows: The steering shaft and the engine mount equals 2.2 mm; The mainframe and rear frame equal 1.9 mm; The supporting parts equal 1.6 mm.

Table 2. Table comparing the weight of motor frame body before and after optimization.

Parameter	Initially	After optimization	Note
Thickness 1	3 mm	2.2 mm	Reduction 27%
Thickness 2	2.5 mm	1.9 mm	Reduction 24%
Thickness 3	2 mm	1.6 mm	Reduction 20%
Mass	7.6 kg	5.8 kg	Reduction 23,7%
Largest displacement	15.88 mm	21.73 mm	Qualified
Maximum stress	227.1 MPa	325.1 MPa	Qualified

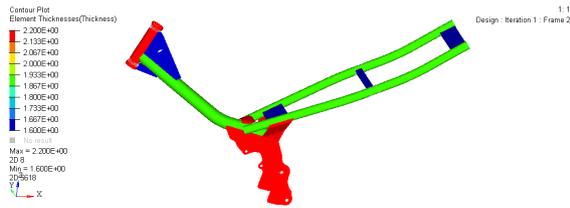


Fig. 17. Results of optimized frame thickness

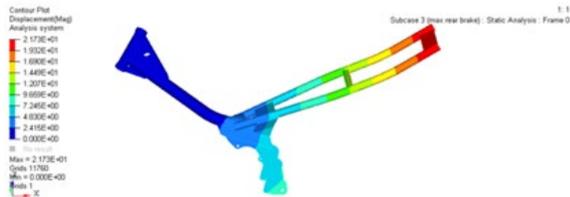


Fig. 18. Chassis displacement after optimization

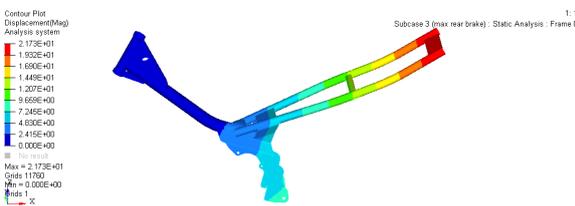


Fig. 19. The stress of the optimized post-frame

#### 4. Conclusion

The research has outlined the importance of optimization in the design process, the basic concepts used in the problem, the way to determine the convergence ability, and the way to find the optimal design of the process.

On that basis, a Free Size Optimization problem (frame thickness) was conducted with the load and boundary conditions such as strength limit and displacement determined in the static problem. The results are outstanding, with a 23.7% reduction in frame weight and maximum stress satisfying the allowable value ( $<385$  MPa). The study results will be

inherited in the optimal methods topology, shape optimization to diversify the designs.

#### Acknowledgments

This research is funded by Hanoi University of Science and Technology (HUST) under grant number T2018-PC-044.

#### References

- [1] Bipin Chadha, Om Prakash Agrawal, Dynamic analysis of flexible multi-body systems using mixed modal and tangent coordinates, *Computers & Structures*, Vol. 31, Issue 6, pp. 1041-1050, 1989.  
[https://doi.org/10.1016/0045-7949\(89\)90289-7](https://doi.org/10.1016/0045-7949(89)90289-7)
- [2] Ján Dižo, Miroslav Blatnický and Alfréd Pavlík, Process of modelling the freight wagon multi-body system and analysing its dynamic properties by means of simulation computations, *Proc. in MATEC Web Conf.*, Vol. 235, pp. 8, 2018.  
<https://doi.org/10.1051/mateconf/201823500027>
- [3] Hun Guo, Taiyong Wang, Zeyu Weng, Weidong Jin, Shaoze Yan, Xuda Qin, Guofeng Wang, Qingjian Liu and Zijiang Wang, The optimization design and analysis of motorcycle frame structure, *Applied Mechanics and Materials*, Vol. 141, pp. 569-573, 2011.  
<https://doi.org/10.4028/www.scientific.net/AMM.141.569>
- [4] Saurabh Rege, Chirag Khatri, Mrudul Nandedkar, Noopur Wagh, Design and analysis of frame for electric motorcycle, *Material Today*, Vol. 5, Issue 5, Part 2, pp. 13563-13573, 2018.  
<https://doi.org/10.1016/j.matpr.2018.02.352>
- [5] Joan Locutura, Comparison between a tubular frame and a beam frame, MS thesis, Departimenti di Ingegneria Meccanica, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, Spain, 2010.
- [6] Vittore Cossalter, Book serial: *Motorcycle Dynamics*, 2nd edition, LULU Publisher, 2006, pp.372.