Methodology for Effective Design of Motorcycle Structures

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Abstract—One of the important tasks that goes before the main stage of motorcycle design is the choice of the motorcycle type. This paper discusses the main types of motorcycles, their characteristics, design features, and geometric parameters that need to be taken into account at the very first stage of product development – the technical proposal. This paper also discusses the forces acting on various parts and components of the motorcycle, and various load cases (when braking/accelerating sharply or turning). Determining the external forces that act on the motorcycle is very important for setting input parameters for calculating topological optimization and generative design. Topological optimization and generative design are the most important technologies for effective design of various motorcycle structures. They are embedded in separate calculation modules of modern CAE programs. Without knowledge of the load conditions and forces that act on various elements of the motorcycle, it is impossible to make an accurate calculation to optimize the mass of the structure or to conduct a generative design for parts and components of the motorcycle. Therefore, the method of effective design consists not only in the application of topological optimization and generative design, but also mainly in the knowledge of design features, geometric parameters, external forces, and load conditions of various types of motorcycles.

Index Terms—stress analysis, strength analysis, input parameters, static forces, dynamic forces, topology optimization, load cases

I. INTRODUCTION

Motorcycles as well as cars are divided into different categories (types): cruise, tourist, sports and others.

When choosing a specific type for designing a motorcycle, you need to take into account its features such as: wheelbase length, trail, weight distribution on the front and rear axles, handling, stability. Handling and stability are closely related to the geometry of the motorcycle. For example, increasing the castor leads to an increase in the trail, which increases the stability of the motorcycle but at the same time reduces the handling of the motorcycle on the road [9]. We'll look at this in more detail in the following sections of the paper.

After determining the type selection, designers consider what loads are experienced by various elements of the motorcycle structure and in what load modes the motorcycle will operate. As the loading modes considered critical variations of loads on the elements of a motorcycle. For example, the critical load for the front steering column occurs at the moment of hard braking of the motorcycle when the rear wheel begins to detach from the road [10, 11].

Knowing the forces acting on the motorcycle elements and load conditions helps you accurately set input parameters for generative design and topological optimization. For example, topological optimization suggests building a model based on an existing model based on several criteria (weight reduction, increased strength) [12, 13]. For generative design, you don't need to have a source model. It is enough to specify the main structural elements and fasteners, and apply loads to them depending on the loading case. After that, generative design will offer many solutions to the problem based on various manufacturing methods. This option is more resource-intensive in contrast to topological optimization. Using this approach can significantly reduce the time required for design development and reduce the weight of the finished product (motorcycle).

Without knowledge of the forces applied to the elements of the motorcycle, we cannot accurately check or create a new motorcycle design. Motorcycle structural elements such as the frame and rear fork using topological optimization or generative design can be too light and cannot withstand external loads or become too heavy. Products such as the frame and rear must be designed so that when an external load is applied, the stresses are the same everywhere. Only in this case are products with a minimum weight obtained.

II. MOTORCYCLE GEOMETRY

Let's start by looking at the standard motorcycle geometry shown in Fig1. It is important to note that the motorcycle itself consists of two structural groups, connected by a steering column [1, 2]. The first group includes the front fork, front wheel, steering wheel, headlights and other parts that move when the steering wheel is turned. The second group includes the frame, electric motor, rear wheel, battery pack and all components that do not move with the control system. The second group also includes the driver.

The axis of the steering column is inclined at an angle α relative to the road. The distance c between the points A of intersection with the road axis of the steering column and B - the contact of the front wheel with the
road is called the offset of the front fork. The average values of the protrusion of the front fork of motorcycles with 80-100mm trail and the angle of inclination of the steering column αn = 60-62°. The running weight of a motorcycle G with driver and luggage is centered at the center of gravity C and distributed between the front and rear wheels into components G1 and G2.

![Figure 1. Main parameters of the motorcycle:](image)

I, II - design groups of the motorcycle; αn is the angle of inclination of the steering column axis; c - trail; L - motorcycle base; G is the running weight of the motorcycle; h, b - coordinates of the center of gravity; l - steering column axis

The trail c is a very important parameter in a motorcycle, it is responsible for the stability of the motorcycle on the road. The stability factor R of a motorcycle is calculated using the formula:

\[ R = \frac{c}{(L+c)} \times 100\% \]

where L is the center distance of the motorcycle wheels, if the value of c takes a negative value, then the motorcycle is not stable while driving [4].

For clarity, consider the geometric parameters of various motorcycle models

The geometric characteristics of the steering column. The values of the angle of the steering column - castor β1 will vary depending on the intended use of the motorcycle. For example, on motorcycles for speedway it is 19°, for sport bikes 21-24°, for touring motorcycles 27-34°.

The trail value controls with the angle of the steering column. For a feeling of good motorcycle handling when zooming in. Trail parameters also vary depending on the type of motorcycle and its wheelbase, ranging from 75-90mm on sport bikes, 90-100mm on sport bikes and up to 120mm on heavy hikers.

The size of the wheelbase is considered depending on the motorcycle. Length 1200 mm for small scooters, 1300 mm for light motorcycles (125 cc), 1350 mm for medium bikes (250 cc) and 1600 mm for large touring motorcycles.

\[ R_p = \frac{c}{(L+c)} \times (N_f/N_r) \]

where \( N_f \) is the load on the front wheel, and \( N_r \) is the load on the rear wheel.

### III. MOTORCYCLE TYPES

Let's consider in more detail each type of motorcycle, its geometric parameters and features. We will compare sport bikes, choppers, cruisers and touring motorcycles in detail. We will also look at the main differences between scooters and motorcycles. The main types of motorcycles are shown in Fig. 2.

![Figure 2. Motorcycle types.](image)

Fig. 2 shows 4 types of motorcycles (sport bikes, choppers, cruisers, touring motorcycles) and a scooter. In the upper left corner – Honda VTR1000F; in the upper right corner – Suzuki GSX-R 750; in the middle left – Harley Davidson 1200 Sportster; in the middle right – Kawasaki VN800; in the lower left corner – Honda XL600V Transalp; in the lower right corner – Aprilia Gulliver 50.

The most important parameters for the problem under study are shown in Table I for sport bikes.

<table>
<thead>
<tr>
<th>Table I. SPORT BIKES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Honda VTR1000F (Fig. 2-a)</strong></td>
</tr>
<tr>
<td>( L ), mm</td>
</tr>
<tr>
<td>1430</td>
</tr>
</tbody>
</table>

| **Suzuki GSX-R 750 (Fig. 2-b)** |
| \( L \), mm | \( \beta_1 \), deg | \( c \), mm | Weight distribution % | \( R_n \) | \( R_p \) |
| 1395 | 24 | 96 | 50.4/49.6 | 6.44 | 6.54 |

Sport bikes have good handling and gain high speed due to forced (high-speed) engines. Landing on a sports bike is tilted forward, for better streamlining, the driver lies with his chest on the tank during the race. Wheels are light-alloy wheels with relatively wide rubber for better grip. A plastic body kit is installed on motorcycles to improve aerodynamic properties. The wheelbase varies from 1390 to 1430 mm. The angle of inclination of the
front fork relative to the vertical is 23-25. Weight distribution in modern sports bikes tends to be 50/50 front and rear respectively.

Table II shows data for choppers.

### TABLE II. CHOPPERS

<table>
<thead>
<tr>
<th>Motorcycle</th>
<th>L, mm</th>
<th>β₁, deg</th>
<th>c, mm</th>
<th>Weight distribution</th>
<th>Rᵣ</th>
<th>Rₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harley Davidson 1200 Sportster</td>
<td>1485</td>
<td>29.6</td>
<td>116.8</td>
<td>45/55</td>
<td>7.29</td>
<td>5.96</td>
</tr>
</tbody>
</table>

Choppers are heavy bikes that provide a low, feet-first ride. This type of motorcycle does not have side fairings. Equipped with low-speed engines. Poor handling (Rₑ = 5.96).

Let’s compare the parameters of the considered types of motorcycles with the cruiser parameters, which are shown in Table III.

### TABLE III. CRUISERS

<table>
<thead>
<tr>
<th>Motorcycle</th>
<th>L, mm</th>
<th>β₁, deg</th>
<th>c, mm</th>
<th>Weight distribution</th>
<th>Rᵣ</th>
<th>Rₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawasaki VN800</td>
<td>1625</td>
<td>34</td>
<td>149</td>
<td>43/57</td>
<td>8.4</td>
<td>6.34</td>
</tr>
</tbody>
</table>

This type of motorcycle is similar to the driver’s landing with choppers. Cruisers have a longer wheelbase compared to choppers and a greater angle of inclination (β₁=34°) of the front fork relative to the vertical. Due to the greater angle of the fork, the trail increases and, as a result, stability on the road increases. Motorcycles of this type have the best stability on the road (Rₑ=8.4). However, at the same time, cruisers lose in handling to sports motorcycles.

Table IV shows data for touring motorcycles.

### TABLE IV. TOURING MOTORCYCLES

<table>
<thead>
<tr>
<th>Motorcycle</th>
<th>L, mm</th>
<th>β₁, deg</th>
<th>c, mm</th>
<th>Weight distribution</th>
<th>Rᵣ</th>
<th>Rₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honda XL600V Transalp</td>
<td>1505</td>
<td>28</td>
<td>108</td>
<td>47.4/52.6</td>
<td>6.7</td>
<td>6.03</td>
</tr>
</tbody>
</table>

Tourist motorcycles are designed for long-distance trips. They have a more comfortable and high landing compared to choppers and cruisers. This type has the most capacious fuel tanks, provides for the installation of additional trunks (small Luggage compartments), which increases the curb weight of the motorcycle. Motorcycles have a long wheelbase: from 1500mm to 1600mm. Lower handling compared to sports motorcycles (Rₑ= 6.03).

At the end of the review, we will consider the scooter parameters, which are shown in Table V.

### TABLE V. SCOOTERS

<table>
<thead>
<tr>
<th>Motorcycle</th>
<th>L, mm</th>
<th>β₁, deg</th>
<th>c, mm</th>
<th>Weight distribution</th>
<th>Rᵣ</th>
<th>Rₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aprilia Gulliver 50</td>
<td>1255</td>
<td>25.5</td>
<td>55</td>
<td>42/58</td>
<td>4.2</td>
<td>3.04</td>
</tr>
</tbody>
</table>

Due to the fact that the engine, CVT (Continuously Variable Transmission), and tank of scooters are located next to the rear wheel, most of the weight is applied to the rear axle. In some scooters, the weight distribution can reach 30/70 in favor of the rear axle. This weight distribution can cause the front wheel to roll over or frequently lift when accelerating sharply. Scooters have poor stability (Rᵣ=4.2) and terrible handling (Rₑ=3.04), which is clearly evident at high speeds. Scooters, unlike motorcycles, have a smaller wheelbase (1200-1255 mm) and smaller wheels of 10-13 inches, which greatly reduces cross-country performance.

### IV. CENTER OF MASS POSITION

The position of the center of the motorcycle’s mass is important in determining the loads that act on different parts of the motorcycle. In Fig. 3 we can see how the center of gravity shifts when the rider sits on the motorcycle. When the rider sits on the motorcycle, the center of mass shifts to the rear axle on all types of motorcycles.

Figure 3. The position of the center of gravity of a motorcycle with and without a driver.

The height of the center of gravity of the motorcycle alone has values ranging from 0.4 to 0.55 m, but the presence of the driver raises it to values ranging from 0.5 to 0.7 m.

The h/L ratio without a driver and with a fully extended suspension ranges from 0.3m to 0.4m; lowest values for cruising motorcycles and scooters, highest for enduro motorcycles.

### V. ACTION OF STATIC AND DYNAMIC FORCES

Consider the static and dynamic forces acting on a motorcycle [5-8]
The action of static forces. The $C_1$ center of gravity of structural group I is located at a distance from the steering column axis.

Because of this, when the motorcycle deviates from the vertical plane by an angle $\beta_1$, a moment is created that turns the fork in the direction of the inclination: $M_1 = G_1 r \sin \beta_1$ (if the driver does not turn the steering wheel), $G_1$ is the gravity force of structural group I. At points B and D (see Fig. 4), horizontal reactions occur due to the deviation of the general center of gravity.

The overall horizontal response is:

$$Y = Y_1 + Y_2 = P_1 \tan \beta_1,$$

where $Y_1$ is the horizontal reaction of the front wheel, $Y_2$ is the horizontal reaction of the rear wheel. Then:

$$Y_1 = G_c b \tan \beta_1; \quad Y_2 = G_c \frac{L-b}{b} \tan \beta_1.$$

![Figure 4. Static diagram of motorcycle](image)

The torque applied to the front fork is defined as:

$$M_1 = Y_1 c \sin \alpha \cos \beta_1 = G_c b \frac{X}{L} \cos \alpha \sin \beta_1;$$

The steering column rises when the front fork is turned, therefore the gravity force of structural group II, concentrated in the center of gravity of $C_II$, prevents the rotation of the control group I nodes. This force is directed along the axis of the steering column and is determined from the conditions of equality of moments relative to point D:

$$P_0 (L+c) \sin \alpha = G_0 X_0; \quad P_0 = G_0 \frac{X}{(L+c) \cos \alpha}$$

Actions of dynamic forces. In addition to static forces, a moving motorcycle is also affected by dynamic forces, which include:

- gyroscopic effect of rotating masses
- centrifugal forces
- reactive forces of rolling tires
- inertial forces of distributed masses

The gyroscopic effect of rotating masses. To determine the gyroscopic moment, the formula is used:

$$M_g = J \omega_1 \omega_2 \sin \alpha \beta,$$

where $J$ is the moment of inertia of the gyroscope; $\omega_1$ - angular speed of gyroscope rotation; $\omega_2$ - angular velocity of gyroscope axis rotation; $\alpha \beta$ is the angle between the direction of the angular velocity vectors. When $\alpha \beta = 90^\circ$, $M_g = J \omega_1 \omega_2$.

![Figure 5. Diagram of the forces that act on the motorcycle when driving along a curve.](image)

Centrifugal forces. When the motorcycle moves on the road at a constant speed in a straight line, the following forces act on the motorcycle: the gravity force of the motorcycle with the driver $G$, (applied at the center of gravity); vertical reactions $Z_1$ and $Z_2$, applied at the points of contact of the wheels with the road and balancing the force of gravity; traction force $P_K = X_2$, directed towards the movement; front wheel rolling resistance $X_1$ against the motion (see Fig. 6). When the motorcycle moves along a curve (that is, when entering a turn), a centrifugal force $P_c$ also appears, applied at the center of gravity and lateral reactions $Y_1$ and $Y_2$, balancing the action of the centrifugal force.

The instantaneous center of curvature $O$ is at the point of intersection of the perpendiculars to the tangents of the road.
drawn in the road plane to the wheels. Front wheel
turning radius:
\[ R_i = \frac{L+c}{\sin \alpha} - c \tan \alpha_1, \]
where \( \alpha_1 \) is the angle of rotation of
the front wheel relative to the rear. Fig. 5 shows that the
wheels roll along a trajectory with different radii, since
\[ R_2 = R \cos \alpha_1 \]
the wheels roll at different speeds.

Centrifugal force when turning:
\[ P = \frac{G v^2}{g R} \]

We can assume that the force \( P \) acts parallel to the axis
OO2, since the size of the segment b is much less than the
value of the radius R.

When the motorcycle is moving under drag force:
\[ X_1 = Z_t = G f \frac{v^2}{R}, \]
\[ X_2 = P; \]

Fig. 5 shows that the reactions \( X_1 \) and \( X_2 \) are in
different directions. When the motorcycle brakes:
\[ X_1 = P_{m1}; \]
\[ X_2 = P_{m2}; \]
The reaction \( Y_1 \) is determined from the equation of the
equilibrium of moments about the axis passing through the
point O2 of the rear wheel touch [3]:
\[ Y_1(L + c_2 \cos \alpha_1 - c) - X_1(L + c_1 \cos \alpha_1) - P_b = 0 \]
\[ Y_1 = P_b + X_1 \sin \alpha_1/L \cos \alpha_1 \]
We find the reaction \( Y_1 \) by projecting the acting forces
line OO2. Let us make the equations:
\[ Y_1 = Y_1 \cos \alpha_1 - X_1 \sin \alpha_1 - P_c = 0; \]
\[ Y_2 = P_c + X_1 \sin \alpha_1 - Y_1 \cos \alpha_1 = P_c + X_1 \sin \alpha_1 - P_c \frac{b}{L}; \]
\[ -X_1 \sin \alpha_1; \]
\[ Y_2 = P_c(1 - \frac{b}{L}) = P_c \frac{a}{L}. \]

In addition to the action of reactions at the points of
support of the motorcycle, the centrifugal force tends to
overturn it relative to these supports in the direction
opposite to the turn. To keep the motorcycle stable, it
must be tilted towards the corner.

According to the equilibrium condition of the motorcycle, the sum of the moments of forces relative to the
O2:O2 axis is zero: \( P_c h_d = G h_d \tan \beta_1 \); but since \( P_c = \frac{G v^2}{g R} \)
then \( \frac{v^2}{R} = \tan \beta_1 \), i.e. the resultant forces \( G \) and \( P_c \) are in the
plane of the motorcycle.

When the motorcycle moves along a curve in the
center of gravity \( C_1 \), a centrifugal force \( P_{c1} \) arises, which
is a component of the total centrifugal force \( P_c \) (see Fig.7).
This component tends to rotate structural group I to its
original position and can be determined by the formula:
\[ P_{c1} = \frac{G_1 v^2}{g R} \]
Moment with which the force \( P_{c1} \) acts on group I in a
plane perpendicular to the steering column axis:
\[ M_{c1} = P_{c1} r \cos \alpha_1 \cos \beta_1 \]
The influence of centrifugal force on group I is
opposite to the influence of static forces.

VI. CONCLUSION

Thus, the research conducted in this article allows us to
draw several important conclusions:
- At the very first stage of development (technical
  proposal), it is important to choose the type of motorcycle.
- Comparative analysis of different types of
  motorcycles shows that sports motorcycles that have the
  best speed characteristics are designed with an emphasis
  on handling. More modern models are made with a 50/50
  weight distribution for better braking properties. Cruisers,
  choppers, and touring motorcycles have their center of
  mass shifted much closer to the rear axle than sport bikes,
  which makes their braking performance worse. But
  cruisers and choppers have better stability on the road
  because of the larger castor. It is important to understand
  that each type of motorcycle is designed for certain
  operating conditions and you always have to choose
  between stability and handling. Sports motorcycles are
  designed for the track, for these conditions, landing is
  important (influence on streamlining) and handling, but
  for the sake of increased handling, they sacrifice stability,
which is compensated by the driver’s experience and control skills. Cruisers and choppers are designed for slow trips over medium distances, so they do not care about increased handling at high speeds, which is why handling is neglected in favor of stability. Tourist motorcycles are designed for comfortable long-distance travel, so they can’t be designed with an uncomfortable sports fit (despite the fact that the sports fit is better in terms of aerodynamic qualities).

- The considered static and dynamic forces will help to accurately set input parameters for generative design and topological optimization

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

O. O. Baryshnikova formulated the research direction, problem statement, and edited the article.

D. V. Strugovshchikov analyzed the design features, loading factors, formed a calculation model, and wrote an article.

All authors had approved the final version.

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